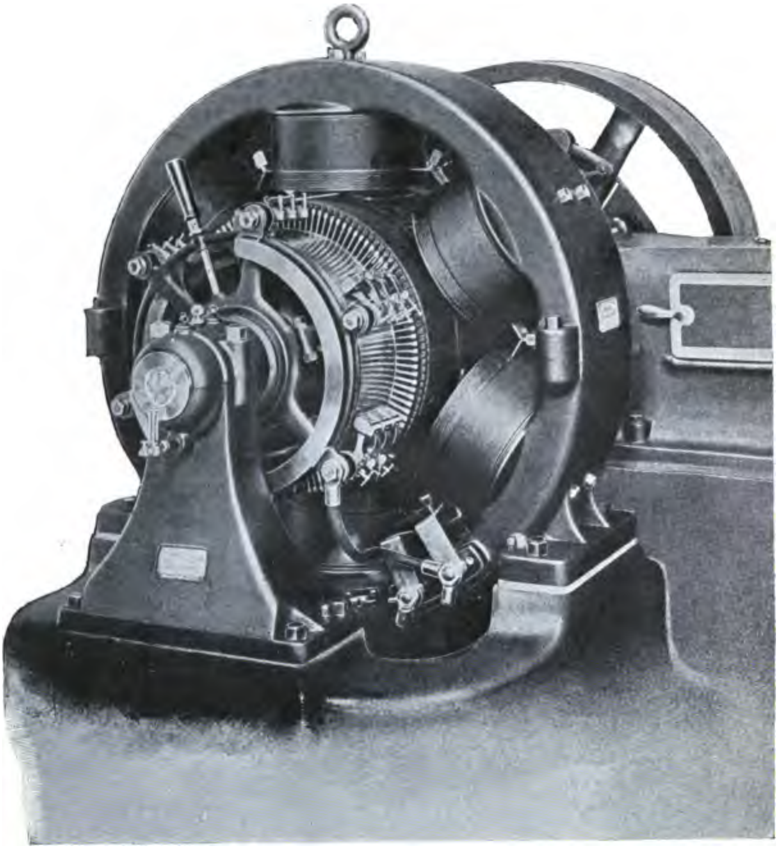

Frontispiece.

DESIGN

OF

ELECTRICAL MACHINERY

A MANUAL FOR THE USE, PRIMARILY, OF STUDENTS IN ELECTRICAL ENGINEERING COURSES

VOL. I

DIRECT CURRENT DYNAMOS

BY

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FIRST EDITION

FIRST THOUSAND

NEW YORK

JOHN WILEY & SONS

LONDON: CHAPMAN & HALL, LIMITED

1912

THE SCIENTIFIC PRESS
ROBERT DRUMMOND AND COMPANY
BROOKLYN, N. Y.

PREFACE

The purpose of this work is to supply a manual on Electrical Design. It contains, what the author believes, will be of the most service to the student who is just entering upon his experience as a designer.

A more comprehensive study of the principles and phenomena underlying the calculations should be made by means of lectures, recitations, through the medium of references, etc.

Good electrical apparatus cannot be designed by any set of rules, and it must be recognized that it is not feasible to develop a real designer in a college course. However, there are certain fundamental scientific principles which can be laid down definitely and taught with precision. The student should bear in mind that, while there is much in this volume that is of practical value, the main object is to present as clearly and briefly as possible the fundamental principles upon which the designer necessarily rests. He also should bear in mind that he cannot expect to get any more than a training that will be of value and assistance to him, if at any time in his later experience he should decide to become a designer.

An electrical designer must also be a mechanical designer. This point is very often overlooked by the beginner. It

is possible to devise some very wonderful designs from an electrical standpoint, but which when the mechanical features are considered are absolutely impractical.

It is the intent of this volume to cover the design of direct-current dynamos and motors; alternating-current generators, synchronous motors, rotary converters, and transformers will be considered in succeeding volumes.

Special attention has been given to the arrangement of the work with regard to the order of the process of making the calculations.

The author has drawn very largely upon information obtained from the Westinghouse Electric and Manufacturing Co. of Pittsburgh, Pa., and from the Electrical Machinery Co. of Minneapolis, Minn., in preparing this work. He desires to acknowledge his indebtedness to the above companies and also to many others whose valuable suggestions have been utilized.

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UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
Jan. 1, 1912.

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DESIGN OF ELECTRICAL MACHINERY

VOLUME I.—DIRECT-CURRENT DYNAMOS

CHAPTER I

THE DESIGN OF DIRECT-CURRENT CONSTANT-POTENTIAL DYNAMOS

The purpose of this chapter is to present a method of dynamo design based primarily upon data derived from machines met with in actual practice, and at the same time bring out the underlying principles of the subject. The student, when designing a dynamo, has before him a very different problem than has the practical engineer. The engineer must not only produce a machine which at a minimum cost, shall have good operating characteristics, high efficiency, durability and last but not least salability; he must also make use of certain standard frames, standard coils, standard molds, standard winding forms, certain available machines, etc., etc.

The completed design is, necessarily, the result of a number of judicious compromises; preliminary assumptions of the values of several fundamental quantities must be made; and upon the judgment here exercised, depends very largely the value of the design.

Given the kilowatt capacity, the voltage at no load and full load, allowable temperature rises and the requirements of the service to which it is to be adapted, we next decide upon the speed.

(A) Speed

If the machine is very small, and we desire to make it bipolar in order to take advantage of cheap construction, on account of the simplicity of the frame and the compact form of armature, a high speed is desirable. The machines of larger capacity are now always made of the multipolar type, even though the speed may be high, owing to the ease with which the armature can be ventilated and the relatively small amount of material and space required for their frames. The advantages of multipolar over bipolar dynamos are about as follows:

(1) Multipolar machines have a more compact and symmetrical form, because the component parts of the magnetic circuit are much smaller than on a bipolar machine, and are evenly spaced around the armature. In a two-pole machine the armature must carry one-half the total flux, while in a four-pole machine the armature cross-section is only required to carry one-fourth the total flux, hence the radial depth need be only one-half as great, thus reducing the weight of the armature. In an eight-pole machine the yoke carries only one-eighth of the total flux, etc. Owing to this subdivision of the flux, the weight of the multipolar magnet frame is much less than that of a two-pole machine.

(2) By the multipolar construction a saving in weight of material is effected in the field magnet as well as in

the armature due to this subdivision of the magnetic circuit.

(3) The ventilation of the armature is much better, since there are as many openings as there are poles; also since a number of small cores have a greater surface than one large core the dissipation of heat is facilitated, so that under the same conditions multipolar machines run cooler than bipolar ones.

(4) The individual parts of the field frame, the field coils and the armature coils are much smaller and more easily handled in the multipolar than in the bipolar type.

(5) As a result of armature reaction it becomes necessary to limit the armature strength at full load to such an amount that it will not interfere too much with the amount and distribution of the magnetic flux due to the field magnets. Experience shows that in ordinary machines the best results are obtained when the armature strength at full load is limited to from 5000 to 8000 ampere turns per pole. This means that for machines of any considerable capacity, several poles will be required.

Assume a certain speed in accordance with Tables I, II, and III.

TABLE I

HIGH-SPEED BELTED DYNAMOS

Kilowatt Capacity.	Revolutions per Minute.
1	1200 to 3000
3	1000 to 2000
10	950 to 1900
20	900 to 1600
40	750 to 1300
60	650 to 1100
100	550 to 800
300	400 to 500
500	350 to 400

TABLE II

LOW-SPEED BELTED DYNAMOS

Kilowatt Capacity.	Revolutions per Minute.
1	700 to 1300
3	650 to 1200
10	600 to 1000
20	500 to 900
40	475 to 700
60	450 to 650
100	400 to 600
300	350 to 450
500	300 to 350

TABLE III

DIRECT-CONNECTED DYNAMOS

Kilowatt Capacity.	Revolutions per Minute.
10	325 to 500
20	275 to 400
40	200 to 350
60	150 to 300
100	120 to 275
500	75 to 125
1000	70 to 125

(B) Number of Poles

If, for reasons already given, a multipolar field magnet has been adopted, the best number of poles must next be decided upon. This is a question (1) of limiting the armature reaction to from 5000 to 8000 ampere turns per pole. (2) Of selecting a size and number of field coils, cores, etc., convenient for making and handling. (3) Of limiting the number of magnetic reversals occurring in the armature core. Direct-current machines are usually designed so that the frequency (pairs of poles×revolutions per second) lies somewhere between 10 and 35 cycles per second. This limits the number of poles, the object being to reduce the

core losses due to hysteresis and eddy currents, the former varying approximately as the 1.6 power and the latter as the square of the frequency. The lower frequency of about 10 or 15 cyles per second applies to low-speed machines for direct connection to engines and the higher frequency of 30 or 35 cycles is adopted for high-speed belt-connected machines.

The relation of the number of poles, to capacity, which conforms with modern practice, is indicated by Table IV.

TABLE IV

CAPACITY AND NUMBER OF POLES

Type.	Kw. Output.	No. of Poles.
High-speed belted...........	0 to 10	2
" "	0 to 100	4
" "	50 to 500	6
Low-speed belted...........	0 to 300	4
" "	10 to 300	6
" "	100 to 500	8
Direct-connected...........	0 to 50	4
"	10 to 300	6
"	100 to 400	8
"	200 to 800	10
"	300 to 1500	12
"	800 to 3000	16

(C) Diameter and Length of Armature

$$D^2L = \frac{(36)(10^4)(1.5+\sqrt{kw})^2}{\text{r.p.m.}}, \qquad \text{(Press)} \tag{1}$$

where D = diameter of armature in cm.
L = length of core in cm.

The above very excellent formula for D^2L is taken from Press's book on dynamo design. It is based upon curves,

(Press, " Dynamo Design," page 6), which show the relationship between capacity and a design coefficient, S, which has a definite physical meaning. It is proportional to the temperature rise and the specific radiative capacity and inversely proportional to the factor giving the armature loss, and the entire loss of efficiency of the machine. The value of this design coefficient is

$$S=\frac{\pi^2\left(1+\frac{\pi\varepsilon}{\sqrt{3}}\right)v\frac{t}{t_0}}{f(100-\eta)},$$

where v = radiating constant for temperature rise t_0

t = final temperature rise;

f = factor of total loss due to energy transformation giving loss radiated by armature;

η = efficiency;

ε = ratio of D to L divided by the number of poles.

The capacity of the machine in watts is then,

$$W=SD^2L(\text{r.p.m.}).$$

Press, in his book on " Dynamo Design " has given curves showing the relationship between W and S for a permissible temperature rise of 40° C., based upon the results of previous designs.

(2) $$D^2L=\frac{kw}{(.064)(\text{r.p.m.})},$$ (Thompson)

where D = diameter of armature in feet,

L = length of core in feet.

The above formula was taken from S. P. Thompson's book on " Design of Dynamos " and as in Press's book he

puts the capacity of the machine equal to a coefficient times the quantity D^2L(r.p.m.), where the coefficient is a sort of a mean, and will be greater for machines of greater specific output, therefore larger in the case of large modern machines than for small or old types. The above formula is given so that it may be used as a check on the others. It is not expected that any of them will give exactly the same results. It is expected that after D and L have been obtained by three different formulas and checked by tables conforming with modern practice that the student will be enabled to obtain reasonable values for D and L at the outset and thus avoid making several re-designs before suitable values are finally obtained.

Steinmetz was the first one to point out the relationship existing between the product of the diameter of the iron core into its length and the capacity output of the machine multiplied by a certain coefficient; or in symbols

$$\frac{(D)(L)}{kw}=C,$$

where C = the Steinmetz coefficient.

The constant C will not vary very widely from 3 where D and L are both given in inches. In large modern machines C will go down to from 1.8 to 2.3 and in small and slow-speed machines will go up to from 4 to 6.

The watts per square inch that can be radiated per unit of peripheral speed is practically a constant quantity, and since the volume of a given armature varies as the square of the diameter and directly as the length, D^2L and not DL should be multiplied by a coefficient in order to get an empirical formula connecting the output of the armature

with its dimensions. Thompson, Press, Arnold and others all do so.

(3) $$\frac{D}{L}=.455p, \qquad \text{(Press)}$$

where p = number of poles.

The above formula is based on square pole shoes. If the pole shoes are square and if they cover 70 per cent of the surface of the armature then the length of core is,

$$L=\frac{.7\pi D}{p}.$$

Solving the above equation we get,

$$\frac{D}{L}=.455p.$$

Obviously a small length of armature turn is to be sought after as well as square pole shoes, as it means less armature resistance and hence less copper loss. However, this condition will not very materially change the ratio of D to L, so that in most cases the ratio obtained by the above formula will not be far off.

(4) $$2^{\frac{p-4}{2}}=\frac{D^2L}{150{,}000}, \qquad \text{(Press)}$$

where p = number of poles.

The above is another empirical formula given by Press involving the number of poles. It is given so that it may be used as a check on what has gone before.

(5) $$D=\frac{(S)(12)}{(\pi)(\text{r.p.m.})},$$

where S = peripheral speed of armature in feet per minute,
L would then be determined from the values obtained above for D^2L.

TABLE V

PERIPHERAL SPEED OF DIRECT-CURRENT ARMATURES

Class.	Peripheral Speed (S).
High-speed belted	3000 to 5000
Low-speed belted	2000 to 3500
Direct-connected	1200 to 3000

The e.m.f. of a dynamo is proportional to the velocity of the moving conductors. The output of a dynamo can be increased by simply increasing its speed. It would therefore seem advisable to run the machine at as high a speed as possible.

The speed is limited because of the friction in the bearings and the strain in the revolving parts due to centrifugal force; also because that part of the heating of the armature caused by the hysteresis and eddy current losses in the iron core must be kept within reasonable limits. Furthermore, if the number of revolutions are fixed by the speed of the engine or otherwise, the diameter of the armature is proportional to the peripheral velocity and an abnormal diameter may be obtained by using a high peripheral speed. Values near the upper limits are chosen for high-speed machines in which the selection of a low peripheral speed would result in too small an armature diameter and a consequent inadequate cooling surface. Values near the lower limits, on the other hand, are chosen for low-speed machines, because too large a peripheral speed would excessively increase the diameter of the armature and would bring the size of the entire machine out of

proportion to its output. Table V will serve as an excellent guide for the unexperienced designer in selecting a proper peripheral speed.

In general, it is advisable to select a value near the average of the two values given for S for the particular class under consideration, as this will give results that will conform closely with those usually used in practice. Tables VI and VII should be used as a check on both D and L and on the ratio of D to L.

TABLE VI (ESTERLINE)

DIAMETERS OF BELTED ARMATURES

Kilowatt Capacity.	Diameter in Inches (Mean).	Ratio of Length to Diameter (Mean).	Kilowatt Capacity.	Diameter in Inches (Mean).	Ratio of Length to Diameter (Mean).
1	7	.65	100	29	.44
1	9	.63	150	34	.40
10	11	.62	300	44	.38
20	14	.59	500	54	.32
50	21	.52			

TABLE VII (ESTERLINE)

DIAMETERS OF DIRECT-CONNECTED ARMATURES

Kilowatt Capacity.	Diameter in Inches (Mean).	Ratio of Length to Diameter (Mean).	Kilowatt Capacity.	Diameter in Inches (Mean).	Ratio of Length to Diameter (Mean).
15	22	.25	500	80	.20
50	27	.25	1000	112	.16
100	34	.22	1400	130	.15
200	47	.22			

An average of the values obtained above for D and L will usually give a well-proportioned machine. Adjustments

of the ratio of D to L, as well as many other points in the design, will have to be made as the work proceeds in order to get certain desired proportions and results.

(D) Breadth and Circumferential Width of Pole

A very good proportion is to make the breadth of the pole core, W, equal to the length of the armature core, L.

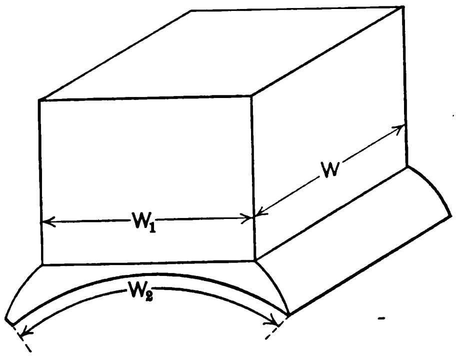


FIG. 1.—Pole Piece of a Direct-current Dynamo.

Assuming a certain percentage of the armature surface, (usually about 70 per cent in new designs), to be covered by the pole shoes we can at once get W_2, the circumferential width of the pole. Another excellent proportion is to make $W_1 = W$. If a round pole core is used the diameter should be very nearly equal to L.

Another excellent form for the pole core is one whose section is a circle with a rectangle in the center. The length of the rectangle is equal to the diameter of the circle and should also be equal to the length of the armature core, L.

It can be used to advantage where it is desired to make the over-all diameter of the machine so small, that it is

impossible to have round or square pole cores. The advantage over the rectangular type is, of course, the saving in field copper due to the shorter mean length of turn.

(E) Flux

Assume an air-gap density in accordance with table VIII.

TABLE VIII

AIR-GAP DENSITIES IN GAUSSES

Kilowatt Capacity.	Cast-iron Poles (Sq.cm.)	Steel or Wrought-iron Poles (Sq.cm.)	Kilowatt Capacity.	Cast-iron Poles (Sq.cm.)	Steel or Wrought-iron Poles (Sq.cm.)
1	3500	5000	100	5500	8000
5	4000	5500	300	5800	8500
10	4300	6300	500	6800	9500
50	5000	7800			

Where the machine is to be used for electrolytic work values somewhat less than the above should be used.

It is desirable that such a value be chosen for the air-gap density as will practically saturate the teeth in order to minimize the distorting effect of the armature reaction on the field. In selecting the values of the air-gap densities, the unexperienced designer must be guided by present practice. Owing to the fact that the magnetic quality of commercial irons has been greatly improved within the last few years, machines are now designed with very much higher flux densities than formerly. The values given in Table VIII correspond with present usage, and is the average air-gap density. Care must be taken not to attempt to oversaturate the teeth.

(6) $$\phi = (W_2)(W)(B),$$

where ϕ = flux per pole;
W = breadth of pole core;
W_2 = circumferential width of pole shoe;
B = air-gap density.

(F) Number of Inductors

(7) $$Z = \frac{(E)(10^8)(p')}{(n)(p)(\phi)},$$

where Z = No. of inductors on the armature;
p = No. of poles;
p' = paths in parallel in the armature;
ϕ = flux per pole;
E = no load e.m.f. of the machine;
n = revolutions per second.

Choose a value of Z as near the calculated value as possible, which will be divisible by numbers which in your judgment would be likely to be the number of inductors per slot and which will also permit you to use a reasonable number of slots which should be a multiple ± 1 of the number of poles. ϕ may then be adjusted accordingly. The number of slots should be taken as large as possible because of the better results obtained from deep and narrow slots than from shallow and wide ones. When a toothed armature is placed in a magnetic field the lines of force concentrate toward the teeth in bunches and thereby destroy the uniformity of the field. If the armature is revolving these bunches of lines of force will be carried along by the teeth until a position is reached in which the lines have been distorted to such a degree that the reluctance of their path has reached the maximum value the magnetomotive force

of the field is able to overcome. They will then snap back into the tooth which is following. As a result of this changing over from one tooth to the next an oscillation of the lines of force is set up which induce eddy currents in the teeth and in the pole faces. In order to prevent excessive heating from this cause the teeth should be made numerous and narrow. In practice it has been found that the length of the air-gap should bear a certain definite relation to the width of the slot. The slot should not be more than from 2 to 4 times the radial length of the air-gap. If the field density is high and if the teeth are pretty well saturated, rather wide slots may be used. Here again the unexperienced designer must be guided by commercial practice. Table IX indicates good practical limits of the number of slots for armatures of different diameters.

A very large number of types of armature windings have been devised. Whole books have been written on this subject alone. Commercial practice, however, has narrowed down to a few very simple windings. It is assumed that the student is familiar with the two usual types of windings, i.e., lap windings and wave windings. If not a special study of these two types must be made at this point before the work is proceeded with. The general form of either one may be found in any one of several textbooks.

The number of paths, p', in parallel in the armature depends on the type of winding used. If a wave winding is used there is almost always, though not necessarily, two paths in parallel through the armature regardless of the number of poles.

The number of slots, coils per slot, and poles will quickly determine the geometrical construction. Certain com-

binations require the omission of one commutator bar. Others require the omission of a coil. Still others cannot be wound at all. It is entirely a question of a geometrical construction which will work out. As a rule this can best be worked out by arranging a table of slot numbers. Only two brushes are required with a wave winding, although there may be as many as there are poles. The wave winding is quite generally used on railway motors on account of the inaccessibility of the lower brushes. It is often used on small motors, especially the 220-volt and 500-volt machines. It is seldom used on generators of any size. Sometimes the same set of coils are wave wound on a four-pole machine for 220 volts and lap wound for 110 volts.

With a lap winding there are usually as many paths in parallel as there are poles, though there may be two or more times this number. There must be as many brushes as there are poles. The general form of the winding may be obtained from any one of several text-books or from your hand-books. The single lap winding in which there are as many paths as there are poles is the most generally used type of winding.

(G) Number of Slots and Commutator Bars

The number of slots should divide into the inductors an integral and preferably an even number of times. Otherwise there will be an odd number of wires per slot and if the slot is of such a width as to accommodate say two wires, the space can be utilized more economically if there are an even number of inductors per slot. It is usually easier to get more combinations of number of wires per layer and number of layers with an even number than with an odd

one. The slots should also be a multiple ± 1 of the number of poles. If there are a fractional number of slots per pole the pitch of an armature coil will necessarily be a little more or less than the pole pitch. Therefore, one coil-side will pass from under the influence of a pole a little after or before the other coil-side. Its e.m.f. is, therefore, changed more gradually. The total air-gap reluctance will also vary less as the armature revolves, if there are a fractional number of slots per pole.

TABLE IX. (ESTERLINE)

NUMBER OF ARMATURE SLOTS

Diameter of Armature in Inches.	Number of Slots.		
	Min.	Mean.	Max.
10	25	45	75
20	50	90	135
30	75	125	196
40	95	160	240
60	125	220	325
100	175	300	450

The number of commutator bars will be either equal to or a multiple of the number of slots unless there are one or more dead coils, which is very unusual. Use 30 to 60 commutator bars per pair of poles for machines up to 250 volts. Use 60 to 90 commutator bars for machines from 250 volts to 600 volts. Wiener gives the following formulae for the minimum number of commutator bars.

For over 100 amp. per path

$$N_c(\text{min.}) = \frac{Ep'}{20}. \tag{8}$$

For 50 to 100 amp. per path

$$N_c(\text{min.}) = \frac{Ep'}{21}. \tag{9}$$

For 20 to 50 amp. per path

$$N_c(\text{min.}) = \frac{Ep'}{23}. \tag{10}$$

For 2 to 5 amp. per path

$$N_c(\text{min.}) = \frac{Ep'}{40}, \tag{11}$$

where N_c = No. of commutator bars;

p' = No. of paths in the armature.

The above determinations fix the number of armature coils, number of slots, number of turns per coil and number of commutator bars.

(H) Dimensions of Armature Inductors

Find the required dimensions of the armature inductors by Formula (12) and see if they can be placed in the space available. Assume a certain percentage shunt field current in accordance with Table X, and add to this the total full-load current output in order to get the total armature current. The current I_a' in one path will be the total current output I divided by the number of paths in the armature.

TABLE X. (ESTERLINE)

SHUNT FIELD CURRENT

(Per cent of full-load current)

Kilowatt Capacity.	Shunt Field Current.	Kilowatt Capacity.	Shunt Field Current.
.25	9	100	2.05
1.0	6.4	200	2.0
5.0	4.5	600	1.48
10.0	3.75	1000	1.3
20.0	3	2000	1.15
40	2.4		

(12) $$D_c^2 = KI_a',$$

where D_c = diameter of armature inductor in mils;

D_c^2 = area in circular mils;

K = number of circular mils per amp. assumed.

For high-speed well-ventilated armatures, $K=450$ to 550. For low-speed well-ventilated armatures, $K=550$ to 650. For poorly ventilated armatures, $K=750$ to 850.

If the inductors are round, the insulation should consist of at least a double cotton covering. The dimensions of the insulated wire may be obtained from a wire table. If rectangular conductors are used allow at least 14 mils for insulation around the individual inductors. About $\frac{1}{32}$ of an inch should be allowed on either side and the bottom of the slot for insulation. There should be placed around each assembled coil at least one layer one-half overlapped of 7-mil tape. In addition to this there is often placed on that portion of the coil which is in the slot a wrapping consisting of one and one-half turns of about 6-mil empire cloth or its equivalent. This wrapping should extend about one-half an inch beyond either end of the armature core.

This wrapping is, of course, put under the cotton or linen tape referred to above. The assembled coil is then dipped in armalac or some other good insulating varnish.

The proper sectional area of the slots is obtained by making the depth of the slot from $2\frac{1}{2}$ to 4 times its width, according to the size of the armature, the lower value referring to very small machines and the larger one to the larger machines. The magnetic density in the teeth must not oversaturate them, and on the other hand they must be pretty well saturated in order to minimize the effects of armature reaction and make good commutation possible.

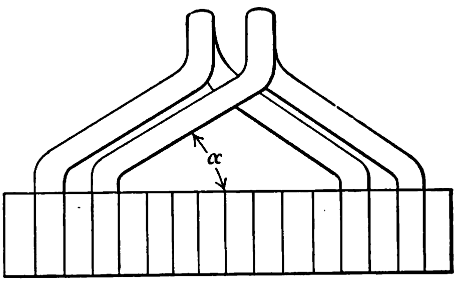


FIG. 2.

In order to get the average length of one turn of a coil lay the coil off to scale, as indicated by Fig. 2. Making a suitable allowance for the length of connections to the commutator calculate the length of conductor in each coil. The total length of conductor on the armature will then be the number of coils times the length of wire in each coil. The resistance of the armature, R_a, will then be

$$(13) \qquad R_a = \frac{\text{resistance of all the wire in series}}{\text{paths}^2}.$$

Angle α varies all the way from 25° to 50°; 30° is a very good value.

The heat loss in the armature will be $I_a{}^2R_a$ and the voltage drop at full load will be

(14) $$V_a = I_aR_a.$$

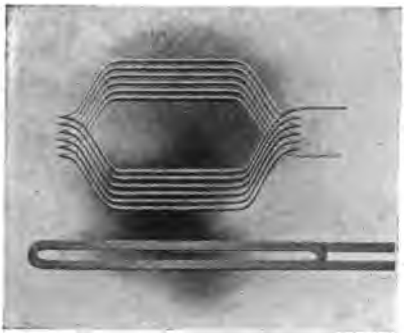


FIG. 3.

(I) Iron Losses in the Armature

(15) $$A_c = \frac{\phi}{(2)(B_c)},$$

where A_c = cross-section of the armature core below the teeth;
B_c = magnetic density in the armature core.

The magnetic density in the core below the teeth should not exceed 70,000 lines of force per square inch; 60,000 to 65,000 are very good values.

(16) $$\text{Depth of core below teeth} = \frac{A_c}{L}.$$

The length and width of the teeth, the area of the core below the teeth and the length of the armature being

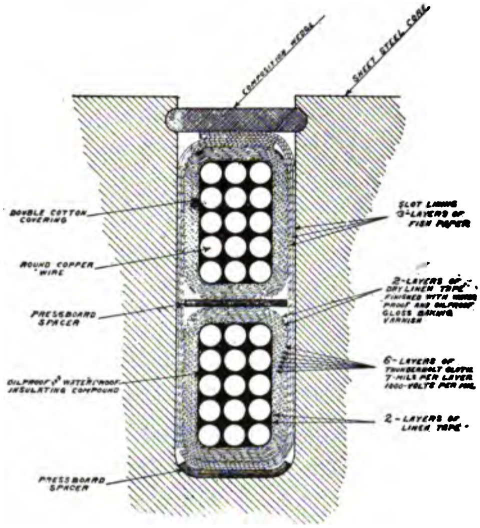


FIG. 4—Detail of Armature Slot and Coil Insulation.

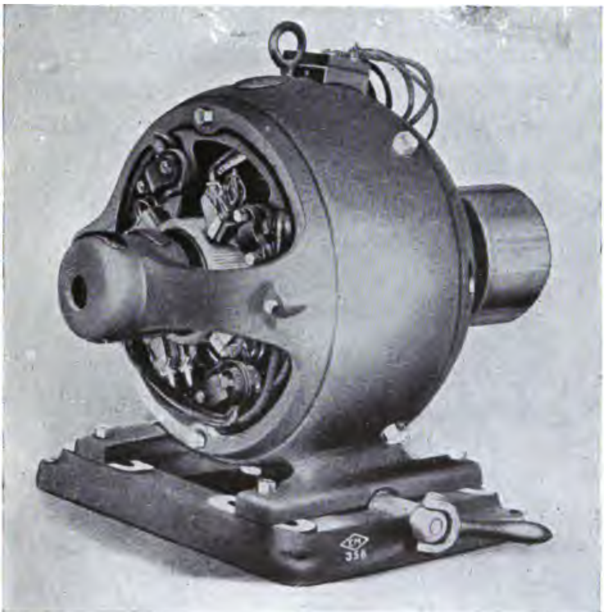


FIG. 5.—Spherical Type Direct-current Motor. (Electric Machinery Co.)

known, the volume of the core in cubic inches may be calculated.

(17) $$W_c=(V_c)(.277),$$

where W_c = weight of core in lbs.;

V_c = volume of core in cu.in.

There are two sources of iron losses in the armature. These sources are, first, the energy spent in continually reversing the magnetism in the armature core as the armature revolves. It is called *hysteresis*. Second, that used in setting up useless currents in the iron. It is called *eddy current loss*.

Although a number of very eminent scientists wrestled for years with the proposition of hysteresis, it remained for an engineer of our time to establish the laws. In 1892, Mr. C. P. Steinmetz gave out the results of his experiments, showing that the energy dissipated by hysteresis varies directly as the frequency of the reversals, directly as the total mass of iron, and approximately, as the 1.6 power of the magnetic density. This law he expressed by the following empirical formula:

(18) $$P_h=\mu B^{1.6}fv,$$

where P_h = hysteresis loss in ergs;
μ = coefficient of hysteresis;
f = frequency in cycles per second;
V = volume of iron in cu.cm.

The coefficient of hysteresis depends upon the physical and chemical qualities of the iron. For good armature

iron it varies from .0012 to .0020. A fair value for good iron is .0015.

Reducing to practical units and inserting .0015 for μ we get,

$$P_c = \frac{(1.24)(B_c^{1.6})(f)(V_c)}{10^{10}}, \tag{19}$$

where P_c = hysteresis loss in the portion of the armature below the teeth;
B_c = magnetic density in lines per square inch;
V_c = volume in cu.in.;
f = frequency in cycles per sec.

$$P_t = \frac{1.24 B_t^{1.6} f V_t}{10^{10}}, \tag{20}$$

where P_t = hysteresis loss in watts in the teeth;
B_t = average density in the teeth;
V_t = volume of the teeth.

$$P_a = P_c + P_t, \tag{21}$$

where P_a = total hysteresis loss in the armature.

From his experiments Steinmetz also found that the energy consumed by eddy currents induced in a body of iron varies as the square of the magnetic density, as the square of the frequency and in direct proportion to the volume of the iron. This he expressed by the following empirical formula:

$$P_e = \eta (B)^2 (f)^2 (V), \tag{22}$$

where P_e = eddy current loss in ergs;
η = eddy current constant,

depending upon the thickness and the specific electrical conductance of the material. For the numerical value of this constant Steinmetz gives the following formula:

$$\eta = \frac{\pi^2}{6} d^2 Y 10^{-9} = 1.645 d^2 Y 10^{-9}, \tag{23}$$

where d = thickness of iron laminae in cm;
Y = electrical conductivity in mhos;
Y = 100,000 for ordinary armature iron.

Inserting the value of η with reference to iron and reducing to practical units the following formula is obtained:

$$P_c' = \frac{(4.2)(d^2)(B_c)^2(f)^2 V_c}{10^{11}}, \tag{24}$$

where P_c' = eddy current loss in that portion of the armature below the teeth in watts;
d = thickness of iron laminations in inches (.014 is a fair value);
B_c = magnetic density in the armature below the teeth;
f = frequency of reversals in cycles per second;
V_c = volume of core below the teeth in cu. ins.

$$P_t' = \frac{(4.2)(d^2)(B_t)^2(f)^2(V_t)}{10^{11}}, \tag{25}$$

where P_t' = eddy current loss in the teeth in watts;
B_t = average density in the teeth;
V_t = volume of the teeth in cu. in.

$$P_A' = P_c' + P_t', \tag{26}$$

where P_A' = total eddy current loss in the armature.

$$P_A'' = P_A + P_A', \tag{27}$$

where P_A'' = total iron loss in the armature.

The American Society for Testing Materials have made a number of experimental determinations of the core losses in various armatures and have published curves in their proceedings which show the relationship between the losses per unit volume of the iron and the product of kilo-gausses and frequency. The author believes it is better for the student to work out the losses by means of the above formulas as he will then get a definite idea as to just how the iron losses are distributed between the various parts of the magnetic circuit, and also just what proportion of them are due to hysteresis and to eddy currents.

(J) Temperature Rise of the Armature

The amount of the total energy consumed in an armature is $I_a^2R_a + P_A''$. The amount of heat liberated depends upon the area of its radiating surface, upon its circumferential velocity and upon the ratio of radiating area to the pole area.

As a result of a very elaborate series of tests made at Cornell University the following conclusions were drawn. (See Transactions A.I.E.E., Vol. X, page 349.)

1. An increase of the temperature of the armature causes an increased radiation of heat per degree rise in temperature, but the ratio of increase diminishes as the temperature increases, and an increase of the amount of heat

generated in the armature increases the temperature of the armature, but less proportionally.

2. An increase in the peripheral velocity increases the amount of heat liberated per degree rise in temperature, but the ratio of increase becomes less with higher speeds.

3. The effect of the field poles is to prevent the radiation of heat.

Mr. Alfred E. Wiener, by combining these results with data and tests of various machines found the values given in Table XI.

TABLE XI

SPECIFIC TEMPERATURE RISE IN ARMATURES

Peripheral velocity in feet per second $= V_p$.	Temperature rise per unit of energy loss, in degrees C. $= t_a$.					
	Ratio of pole area to total radiating surface.					
	.8	.7	.6	.5	.4	.3
0	110°	100°	95°	90°	86°	83°
10	80	74	70	67	64	62
20	64	61	58	56	54	52
30	55	53	51	49	48	46
40	50	48	47	46	45	44
50	48	47	46	45	44	43
75	47	46	45	44	43	42
100	46	45	44	43	42	41
150	45	44	43	42	41	40

The product of the specific temperature increase and the specific loss gives the rise in temperature.

$$T_a = t_a \frac{P_A'' + I_A^2 R_A}{S_A}, \tag{28}$$

where T_a = rise in temperature of armature in degrees centigrade;

t_a = specific temperature increase,

S_A = total radiating surface of armature in square inches.

$P_A'' + I_A^2 R_A$ = total energy loss in the armature,

$\frac{P_A'' + I_A^2 R_A}{S_A}$ = specific energy loss.

The radiating or cooling surface of an armature is that portion of its superficial area which is in direct contact with the surrounding air. The shape and construction of the armature and the size and arrangement of the field determine this radiating portion of the armature.

(29) $$S_A = S + S_1 + S_2 + S_3,$$

where S = external cylindrical surface of the armature in square inches;

S_1 = internal cylindrical surface of the armature core in square inches;

S_2 = radiating surface of the core and conductors at the two ends of the armature;

S_3 = radiating surface presented by one side of a ventilating duct.

(30) $$V_p = \frac{SV + S_1V_1 + S_2V_2 + S_3V_3}{S + S_1 + S_2 + S_3},$$

where V_p = average peripheral velocity of the radiating surface of the armature;

V = peripheral velocity of S;

V_1 = peripheral velocity of S_1;

V_2 = peripheral velocity of S_2;

V_3 = peripheral velocity of S_3.

If the temperature rise does not come up to nearly the specified value, the current density in the armature inductors may be increased. If the temperature rise is too high it will be necessary to either increase the area of the armature inductors, or increase the radiating surface by putting in more air ducts, or by doing both.

FIG. 6.—Armature of a Direct-current Dynamo. (Electric Machinery Co.)

The Standardization Committee of the American Institute of Electrical Engineers recommends that the maximum temperature elevation of the field and armature should be 50° C., of the commutator and brushes 55° C., and of the bearings and other parts of the machine 40° C.

(K) Commutator and Brushes

$$D_c = \frac{(V_c)(12)}{(\pi)(\text{r.p.m.})}, \tag{31}$$

where D_c = diameter of commutator in inches;

V_c = peripheral velocity in feet per minute.

The peripheral velocity of the commutator should not exceed 3500 feet per minute; about 2200 feet per minute being a good average value.

On the other hand the diameter should be such that the segments will present a sufficient surface to the brushes and yet not be so wide as to require an excess of copper or brushes of unusual dimensions.

If we confine ourselves to the simple case, in which a brush is never in contact simultaneously with more than two segments and neglect the influence of neighboring

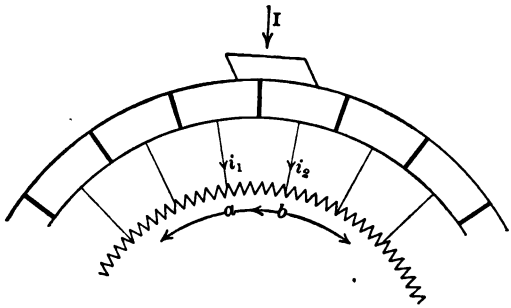


FIG. 7.

wires which may be undergoing commutation at the same time under another brush, we can easily see why the effects of self-induction of the short-circuited coils is the stumbling block to sparkless commutation.

Assume that the short-circuited coil has no self-induction and that commutation occurs in the magnetic neutral axis. Let the width of the brush be that of one segment.

The current I flows from the external circuit to the brush and there divides into two parts. Just before the coil *ab* reaches the position of short circuit it is carrying a current of $\frac{1}{2}I$ in one direction. During the time *ab* is

short-circuited which is equal to the time required for one segment to pass under the brush this current must change from $\frac{1}{2}I$ in a given direction to $\frac{1}{2}I$ in the opposite direction. Practically all of the resistance in the circuit through the short-circuited coil *ab* is that due to the contact resistance of the brush with the commutator segments. If we let R_1 represent the contact resistance of the brush and the segment coming under it, R_2 the contact resistance of the brush and the segment leaving it, and R the contact resistance of the whole brush, then evidently,

$$R_1 = R\frac{T}{t}, \qquad R_2 = R\frac{T}{T-t},$$

where T = the time of commutation,

t = the time, taken from the moment of short-circuit.

Evidently when $t=\frac{1}{2}T$, R_1 and R_2 are equal and $i_1 = i_2$; when $t=0$, $i_1=0$, and $i_2=I$; when $t=T$, $i_1=I$ and $i_2=0$. The area of contact and therefore the resistance of the trailing tip of the brush is proportional to $T-t$. Since both the current and the contact resistance are proportional to $T-t$, it follows that the current density in the trailing tip is constant. There is, therefore, no sparking, since the current in the trailing tip decreases uniformly, and when the brush leaves the segment has fallen to zero.

However, conditions are not as outlined above, because the short-circuited coil produces lines of force which collapse as the current decreases and are re-established in the opposite direction as the current builds up in the reverse direction. i_1 is no longer equal to i_2 when the $t=\frac{1}{2}T$, but at a much later time. Therefore, the current density in the trailing

tip increases due to the self-induction of the short-circuited coil during the period of short-circuit.

In order to obtain sparkless commutation it is therefore, necessary to place the brushes in such a position that when the coil *ab* reaches the position of short-circuit it shall have just arrived in a field of such a direction and strength as to be able to induce an e.m.f. in it which will just counteract the e.m.f. of self-induction due to the current changing from $+\frac{1}{2}I$ to $-\frac{1}{2}I$. It is of prime importance to reduce the self-induction of the coils as much as possible. For this reason armature slots are open and coils of as few turns as possible are used. It further shows the unfavorable effect of high speed in reducing the time available for commutation. This may be counteracted by using wide brushes but here again are limitations because the more segments we cover with a brush the more coils we short-circuit. A brush should be at least as wide as one segment in order to lengthen the time of commutation. However, it is usually found necessary to make it considerably wider than one segment in order to get the necessary brush area, without making the commutator any longer than is necessary in order to provide sufficient radiating surface. It also follows from the above that carbon brushes are usually preferable to copper brushes. Carbon brushes have more contact resistance and a lower current density than copper brushes. There is, therefore, a lesser variation in current density in the trailing tip under unfavorable conditions. In electrolytic generators, however, where the currents are very large and the pressure small, carbon brushes cannot be used on account of the pressure drop which they will introduce.

The number of segments to be used varies with the design

and the style of winding used. The allowable difference of potential between the commutator segments is governed by the reactance voltage of the coils short-circuited, and varies from 20 volts or more in small 500-volt machines to 2 volts or less in very large 110-volt machines. Use 15 to 30 segments per pole for machines from 110 to 250 volts. Small 4-pole 110-volt machines may have as few as 10 segments per pole. Use 30 to 45 segments per pole for 400- to 600-volt machines. Machines used for electrolytic work, where a large current at a very low voltage is desired, often have only 6 to 10 segments per pole.

The voltage reactance of the coils short-circuited by a brush should not exceed two-thirds of the average voltage between segments, otherwise the brushes will have to be shifted too far forward in order to get the short-circuited coils into a sufficiently strong commutating field. In fact, with more than 50 per cent overload it would be impossible to find a commutating field even under the influence of a pole. The insulation between the segments varies from 25 to 40 mils, that below the segments from 60 to 120 mils, and at the ends of the segments from 90 to 130 mils.

Assume that a brush will cover from 2 to 4 segments depending principally on which number will give you a good width of brush. Assume a current density of from 25 to 40 amps. per square inch of brush contact.

$$A_b = \frac{I_a' \times 2}{\text{current density}}, \tag{32}$$

where A_b = area one set of brushes.

$$L_b = \frac{A_b}{\text{width}}, \tag{33}$$

where L_b = length of one set of brushes.

Divide the above length up between a suitable number of brushes.

The length of the commutator will then be the width of the set of brushes plus a proper allowance for space between the brushes and for staggering.

The ohms per square inch of brush contact may be obtained from Table XII.

TABLE XII

BRUSH CONTACT RESISTANCE

Pounds per Square Inch.	Ohms per Square Inch of Brush Contact when Current Density is 30 Amps. per Square Inch (+ and − contact) $=R_b'$.	Pounds per Square Inch.	Ohms per Square Inch of Brush Contact when Current Density is 30 Amps. per Square Inch (+ and − Contact) $=R_b'$.
.6	.086	1.6	.058
.8	.078	1.8	.056
1.0	.071	2.0	.053
1.2	.066	2.4	.050
1.4	.062	2.8	.049
1.5	.066	3.0	.049

$$R_b = \frac{R_b'}{A_b}, \tag{34}$$

where R_b = resistance of one set + and one set of − brushes in series;

A_b = area in square inches of the brushes in one set.

The drop in voltage due to the brush contact resistance will be:

$$E_b = (I_a')(2)(R_b), \tag{35}$$

where E_b = drop due to brush contact;

I_a' = current per path.

The resistance between the commutator and the terminals of the machine will be (not including the series field and neglecting the lead wires which offer practically no resistance):

$$R_b'' = \frac{2R_b}{s}, \tag{36}$$

where s = number of " sets " of brushes;

R_b'' = total brush contact resistance (practically is the resistance from the commutator to armature terminals).

The I^2R loss in the brush contacts will then be,

$$W_b' = I_a^2 R_b'', \tag{37}$$

where I_a = total armature current;

W_b' = watts lost in brush contact resistance.

$$W_f' = \frac{(b')(A_b')(\pi)(D_c)(\alpha)(746)(\text{r.p.m.})}{(12)(33000)}. \tag{38}$$

where W_f' = loss in watts due to brush friction;

b' = brush pressure in lbs. per square inch (varies from 1 to 3. 1.5 is a good value);

A_b' = total contact area of the brushes;

D_c = diameter of the commutator in inches;

α = coefficient of friction (0.3 is a fair value for carbon brushes).

$$W_b = W_b' + W_f', \tag{39}$$

where W_b = total brush losses in watts.

So much copper has to be provided to make the commutator wear well that the I^2R losses in the commutator are

negligible. W_b therefore practically represents the losses between the commutator connections and the terminals of the machine, not including the series windings.

The temperature rise of the commutator in degrees C. above the air will be,

$$T_c = \frac{W_b}{S_c} t_c, \tag{40}$$

where S_c = radiating surface of the commutator brushes and brush-holders in square inches;

t_c = rise of temperature per unit of specific energy. (See Table XIII.)

TABLE XIII

SPECIFIC TEMPERATURE RISE OF COMMUTATORS

Average Peripheral Velocity of S_c in Feet per Minute.	Rise of Temperature per Unit Specific Energy Loss in Degrees C. $= t_c$.	Average Peripheral Velocity of S_c in Feet per Minute.	Rise of Temperature per Unit Specific Energy Loss in Degrees C. $= t_c$.
600	38	2100	28
900	35	2400	27
1200	32	3000	26
1500	30	3600	25
1800	29		

If the temperature rise exceeds 55° C. for continuous operation at normal load, the radiating surface should be increased either by increasing the outside diameter, by making the commutator hub hollow, or increasing the length.

(L) Reactance Voltage

A large number of experiments by Hobart on a number of machines showed that an armature coil in the point of the field in which it is ordinarily commutated will set up an

average of 20 maxwells per ampere turn per inch of gross length of the armature core.

(41) $$\phi_r = (L)(20)(2)(n)(t),$$

where ϕ_r = total flux linked by the short-circuited coils;
n = number of coils short-circuited by one brush;
t = number of turns per coil;
L = length of armature core in inches.

The factor 2 is inserted because there are two coils appearing in the same slot short-circuited by adjacent brushes at the same instant, and the flux set up by both is linked by the turns of either.

The inductance in henrys of the short-circuited coils will then be,

(42) $$h = \frac{\phi_r t}{10^8},$$

where h = induction in henrys;
t = number of turns per coil.

The time during which a reversal takes place is that required for one commutator segment to pass under a brush and is,

(43) $$T = \frac{(W_c)(60)}{(\pi)(D_c)(\text{r.p.m.})},$$

where T = time of commutation;
W_c = circumferential width of a brush in inches;
D_c = diameter of commutator in inches.

Two reversals are required to make a cycle, hence the frequency of commutation, f_c, is,

(44) $$f_c = \frac{1}{2T},$$

where f_c = frequency of commutation in cycles per second. The reactance voltage will then be,

$$E_r = 2\pi f_c h I_a', \tag{45}$$

where E_r = reactance voltage;
h = inductance in henrys;
I_a' = current per path in the armature in amperes.

This must not be more than two-thirds the average voltage developed between commutator segments, and preferably should be very much less than this. In case E_r comes out too high it is usually lowered by decreasing the number of turns between segments.

(M) Diameter of Shaft

The diameter of the shaft within the core may be found by the formula,

$$D_c' = K_1 \sqrt[4]{\frac{W}{\text{r.p.m.}}}, \tag{46}$$

where W = output of the machine in watts;
K_1 = constant depending on the output of the machine. (See Table XIV.)

TABLE XIV

SHAFTS CONSTANTS

Capacity in Kilowatts.	K_1.	Capacity in Kilowatts.	K_1.
1	.9	100	1.3
5	1.0	200	1.4
10	1.1	500	1.5
50	1.2	1000	1.6

The diameter of the bearing portion of the shaft may be obtained from the formula:

$$D_b = 0.8 K_1 \sqrt[4]{\frac{W}{\text{r.p.m.}}}, \tag{47}$$

where D_b = diameter of the bearing portion of the shaft in inches.

The length of the bearing may be found from the formula:

$$L_b = K_2 D_b \sqrt{\text{r.p.m.}}, \tag{48}$$

where L_b = length of the wearing portion of the bearing in inches;

K_2 = constant (see Table XV).

TABLE XV. (ESTERLINE)

Capacity in Kilowatts.	K_2. High Speed.	K_2. Low Speed.
1	.075	.100
5	.100	.150
10	.115	.175
50	.125	.200
100	.150	.225
1000	.200	.275

FIG. 8.—Bearings Used on High Speed Machines.

(N) Dimensions of Pole Core

If ϕ is the flux in the air-gap under one pole at no load, the corresponding full load value of the flux in the pole core will be:

$$\phi' = \phi\lambda, \tag{49}$$

where λ = leakage coefficient. (See Table XVI.)

TABLE XVI. (ESTERLINE)

LEAKAGE COEFFICIENTS FOR MULTIPOLAR FIELDS

Capacity in Kilowatts.	Leakage Coefficient.	Capacity in Kilowatts.	Leakage Coefficient.
1	1.35	50	1.14
2	1.25	100	1.12
5	1.20	500	1.09
10	1.16	1000	1.08
25	1.15		

$$A_p = \frac{\phi'}{B_p}, \tag{50}$$

where A_p = area of pole core;
B_p = magnetic density in the pole core.

If the breadth, W (see Fig. 1), is made equal to the length of the armature, which accords with usual practice, the width, W_2, will be:

$$W_2 = \frac{A_p}{W}. \tag{51}$$

This formula applies to a rectangular pole core. If a round pole core is used the diameter should be made, as

nearly as possible, equal to the length of the armature core. In any case the pole shoe, if there is one, should be as wide as the armature core is long and should cover not less than approximately 60 per cent, nor more than approximately 80 per cent of the circumference of the armature.

If the core is laminated, an allowance of about 10 per cent should be made for the insulation between the laminations. If sheet steel or wrought iron is used in the pole core, the magnetic density should ordinarily be from 85,000 to 90,000 lines of force per square inch. If cast-iron poles are employed, a magnetic density of from 45,000 to 50,000 lines of force per square inch is usually about right.

(O) Length of Pole Core

It must be sufficiently long to allow for radiation and for the accommodation of the windings. A certain percentage field current was assumed in accordance with Table X.

(52) $$W_s = (W) \text{ (per cent shunt field current assumed)},$$

where W_s = shunt field loss in watts;
W = capacity of the machine in watts.

(53) $$W_s' = \frac{W_s}{p},$$

where p = number of poles;
W_s' = shunt field loss per pole.

(54) $$S_p = 2(a+b)l,$$

where S_p = total radiating surface of the shunt field coil in square inches.

Experiments show that heat is radiated away from the surface b' almost as fast as from a or b due to the fact that iron is a much better conductor of heat than air. For high-speed belted machines provide 3 to 3.5 sq. ins. total radiating surface per watt loss. For low-speed belted machines there should be provided from 4 to 5.4 sq. ins. per watt loss.

We now know approximately the watts shunt field loss per pole and the number of square inches of radiating surface

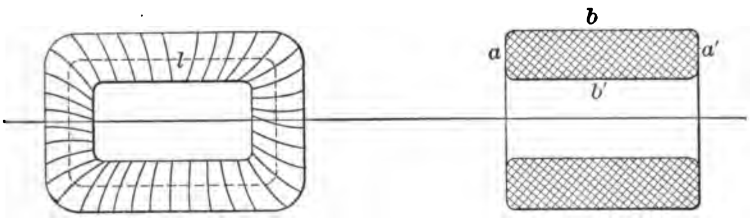


FIG. 9.—Field Coil of Direct-current Dynamo.

required on the shunt field coil but we do not know the size of wire or the number of turns.

In order to proceed with the design, assume that a definite amount, say 20 per cent of the total e.m.f., is taken up by the shunt field rheostat. The voltage on one shunt field coil will then be

(55) $$E_f = \frac{(E)(.8)}{p}.$$

where E = voltage of machine;

p = No. of poles.

Determine the size of shunt field wire by allowing from 800 to 1200 circular mils per ampere; 1000 is a good value for a new design.

Choose a size of wire from a wire table which is as near the calculated size as possible. Use not less than double cotton covering for the minor insulation.

As an estimate of the number of turns for a preliminary design may be made as follows: the resistance (hot) of the shunt field coil will be,

$$R_f=\frac{E_f}{I_f}, \tag{56}$$

where I_f = shunt field current as taken from Table X;
E_f = voltage on one shunt field coil.

Allow a reasonable thickness for major insulation (say $\frac{1}{4}$ to $\frac{3}{8}$ inches), and determine the length of an inside field turn. Allow a reasonable depth of winding (which will be corrected later), and calculate the length (l) of a mean turn. Knowing, approximately, the resistance of the shunt field, the length of a mean turn and the size of wire, we can at once determine the approximate number of turns on the shunt field coil.

Next, make the pole core long enough to accommodate a shunt field coil, having what you consider a reasonable depth of winding, a, and long enough, b, to give the required number of square inches per watt loss in the coil. Other designs should be consulted before estimating the depth of the shunt field winding.

If the machine is to be compound wound and it is thought desirable to place the series field coil next to the pole core and below the shunt field coil, it will be necessary to add from 15 to 40 per cent to the length determined above in order to also provide room for the series field coil. Sometimes the series field coil is made of bare copper strap wound on edge with the turns separated from each other by wedges.

The coil is then placed outside of the shunt field coil and next the yoke, which is space that is ordinarily not used for anything. This gives a much shorter pole core and a higher temperature rise may be allowed since even if the coil does get hot there is no insulation to carbonize. It is an excellent design.

If the space available for the windings proves to be either too small or too large the length of pole core chosen above will, of course, have to be adjusted accordingly.

(P) Yoke

The cross-section of the yoke for a multipolar machine will be:

$$A_y = \frac{\phi'}{2B_y}, \tag{57}$$

where ϕ' = flux per pole;

B_y = magnetic density in the yoke.

If the yoke and pole are made of the same material, the magnetic density employed in the yoke is usually only 80 to 90 per cent of what it is in the pole core. For a cast-steel yoke use 65,000 to 75,000 lines of force per square inch. For a cast-iron yoke 40,000 to 45,000.

(Q) Air-gap

$$\text{Air-gap (max.)} = \frac{D}{50+D} \qquad \text{(Press)} \tag{58}$$

$$\text{Air-gap (min.)} = \frac{D}{200+D} \qquad \text{(Press)} \tag{59}$$

where D = diameter of armature in cm.

For ordinary purposes an average of the above values will be about right.

(R) Ampere Turns

Lay off the magnetic circuit to scale on a drawing board and prepare a table as follows:

Part.	Magnetic Density.	Length of Mean Line.	Ampere Turns per Inch.	Total Ampere Turns.
Yoke.........				
Pole core......				
Air-gap.......				
Teeth........				
Arm core......				
Total......				

As the quantities indicated are obtained, insert them in the above table. Changes made necessary by other adjustments in the design can quickly and very easily be made by referring back to this table.

The ampere turns may be obtained either from tables or by the following formulæ:

(60) $$NI_m = \frac{.8\phi_m L_m}{A_m y},$$

where NI_m = ampere turns necessary to force the flux through the part of the circuit under consideration;

ϕ_m = corresponding number of lines of force;

L_m = mean length in cms. of the part of the circuit under consideration;

A_m = corresponding area in sq.cm.;

y = permeability of the magnetic material. (See Table XVII.)

If the dimensions are given in inches, then,

$$NI_m = \frac{.3133\phi_m L_m}{A_m y}. \tag{61}$$

TABLE XVII

PERMEABILITY OF DIFFERENT KINDS OF IRON AT VARIOUS MAGNETIZATIONS

Density Lines per Square Inch.	Annealed Wrought Iron.	Commercial Wrought Iron.	Gray Cast Iron.	Cast Steel	Sheet Steel
20000	2600	1800	850	2500	2400
25000	2900	2000	800	2600	2500
30000	3000	2100	600	2750	2625
35000	2950	2150	400	2700	2750
40000	2900	2130	250	2650	2860
45000	2800	2100	140	2600	2975
50000	2650	2050	110	2475	3100
55000	2500	1880	90	2300	3000
60000	2300	1850	70	2100	2900
65000	2100	1700	50	1800	2775
70000	1800	1550	35	1475	2660
75000	1500	1400	25	1160	2500
80000	1200	1250	20	1000	2400
85000	1000	1100	15	850	1900
90000	800	900	12	750	1400
95000	530	680	10	690	1100
100000	360	500	9	590	900
105000	260	350	...	525	480
110000	180	260	...	475	310
115000	120	190	...	425	178
120000	80	150	...	390	145
125000	50	120	...	350	99
130000	30	100	...	250	69
135000	20	85	...	150	40
140000	15	75	...	100	20

By means of Eq. (61), find the number of ampere turns required: 1. To force the no-load flux through the yoke; 2. Through the pole core; 3. Through the air-gap;

4. Through the teeth; 5. Through the armature core. Add these five values together, thus obtaining the no-load ampere turns which is also the number of ampere turns on each shunt field coil.

Divide the no-load ampere turns as obtained above by the shunt field current (Table X), to get the number of turns on each shunt field coil. Multiply this by the mean length of one turn in feet and get L_f the total length of copper wire in feet in each coil. The number of turns here obtained and the total length of wire, L_f, will vary more or less from the values obtained in our preliminary calculations. It will therefore now be necessary to re-design the shunt field coil and to make such changes as are required to give it the proper proportions. It should be checked up for temperature rise by the following formula which is based on Timmerman's experiments at Cornell University. (See Trans. Amer. Inst. Elec. Engrs., p. 342, Vol. X.)

$$T_s = \frac{83 W_s'}{S_p}, \tag{62}$$

where T_s = temperature rise of the shunt field coil in degrees C.;

W_s' = loss per pole in watts;

S_p = total radiating surface of the coil in square inches.

T_s should not exceed 40° C. If it is very much over 40° C., it will be necessary to re-design the coil.

(S) Series Field Coils

The armature demagnetizing turns per pole will be:

$$\text{Demagnetizing turns} = N_a I_a' \frac{2\beta}{\pi}, \tag{63}$$

where N_a = number of armature turns per pole;
I_a' = armature current per path;
β = angle of brush lead in radians.

In ordinary machines two-thirds the angular distance between a point midway between the pole tips and a pole tip would be a fair value for β.

The armature cross-magnetizing turns per pole will then be:

(64) $$\text{Cross-magnetizing turns} = N_a I_a' \left(1 - \frac{2\beta}{\pi}\right).$$

In order to get the total number of ampere turns necessary to give the same induced e.m.f. at full load as at no load, add the demagnetizing ampere turns directly to the

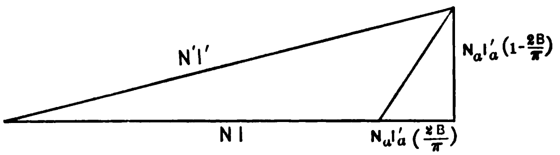


FIG. 10.

no-load ampere turns, and add the cross-magnetizing turns at right angles.

(65) $$N'I' = \sqrt{\left[NI + N_a I_a' \left(\frac{2\beta}{\pi}\right)\right]^2 + \left[N_a I_a' \left(1 - \frac{2\beta}{\pi}\right)\right]^2},$$

where $N'I'$ = total number of ampere turns necessary to maintain the same induced voltage in the armature at full load as at no load;
NI = no load ampere turns = shunt field ampere turns as calculated above.

(66) $$N_s I_s = N'I' - NI \text{ (very closely)},$$

where N_sI_s = number of ampere turns necessary to provide on the series field coil in order to maintain the same induced voltage at full load as at no load.

If the machine is to be compounded not more than say 10 per cent, it will be sufficiently accurate for practical purposes to take the percentage compounding of $N'I'$ as the number of ampere turns additional to the above Eq. (66) to be furnished by the series field. This is on the assumption that the increase in the shunt field ampere turns due to the increased e.m.f. applied to the shunt field terminals as the voltage increases just about offsets the increase in the number of ampere turns required on account of the lower permeability, due to the increased magnetic density. This approximation will be found to hold quite closely in commercial machines. Provide 25 per cent, at least, more series turns than the calculated number. When the machine is tested a "jumper" (resistance in multiple) is provided which will reduce the compounding to the desired amount.

If a more exact solution is required it will be necessary to calculate the required full-load flux and full-load densities in the various parts of the magnetic circuit and then recalculate the ampere turns necessary to give this required full-load voltage. The difference between the no-load ampere turns and the full-load ampere turns would then be the number required in the series field.

(67) $$N_tI_t = N'I' + K_4(N'I')$$

where N_tI_t = total number of ampere turns;

K_4 = per cent compounding.

(68) $$N_s'I_s' = N_tI_t - NI,$$

where $N_s'I_s'$ = total number of series ampere turns;
NI = total number no-load ampere turns.

$$N_s = \frac{N_s'I_s'}{I_s'}, \tag{69}$$

where N_s' = number of series turns;
I_s' = series field current.

Determine the size of wire in the series field by using from 750 to 850 circular mils per ampere. Check the temperature rise of the series field coil by Eq. (62).

The cross magnetization due to the current in the armature can be very effectively neutralized by means of auxiliary poles placed in the neutral zone. These poles are excited by the armature current and can, therefore, be so designed as to just neutralize the cross-magnetizing effect of the armature at all loads, and in addition produce a commutating field at the geometrical neutral. The brushes can then be fixed in the geometrical neutral axis. In calculating the required number of ampere turns per pole on the inter-poles, provision must be made for a sufficient number to just offset the armature ampere turns and in addition to produce enough lines of force to set up in the short-circuited coils an e.m.f. equal to that due to their self-induction. If inter-poles are provided the main poles usually cover somewhat less than 70 per cent of the armature surface.

The commutating poles may be either cast steel or built up of sheet-steel laminations bolted to a seating on the yoke exactly in the middle of the interpolar space as shown in Fig. 11. As a rule no pole shoes are provided on the inter-poles and the length of the polar arc is such that during

the whole period of short-circuit of a coil by the brush it cuts the flux due to the auxiliary pole.

A narrow commutating pole arc is desired, so as to get as large a space as possible between the auxiliary and main poles, thus improving the ventilation and ensuring a lower temperature rise. It also results in a smaller leakage of flux. On the other hand, as far as commutation is concerned, it is essential that the polar arc be not too small, otherwise

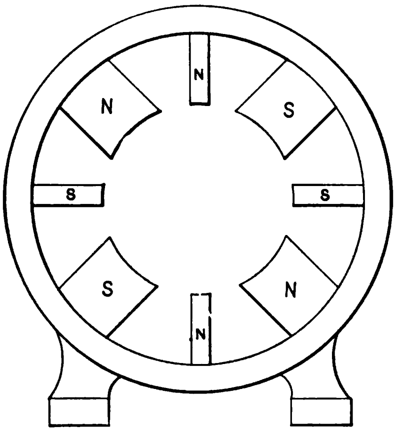


FIG. 11.—Field Magnet Frame with Inter-poles.

there will be rapid fluctuations in the strength of the auxiliary field.

Suppose for example that the polar arc is the same width as an armature tooth, also that the slots and teeth are the same width. It is very evident that the magnetic reluctance of the path of the auxiliary flux is very much greater when the coil is in the position B than when in the position A. Also part of the short-circuited coils may lie outside of the influence of the auxiliary field.

This bad feature is improved as the length of the air-gap is increased, the variation in the flux being less and the

fringing effect greater. Motors having very narrow commutating poles are very apt to hunt due to this oscillatory variation in the strength of the field even though the load is constant. Usually at least two or three segments are under a brush at once. The polar arc should be about 50 per cent larger than this. Professor Arnold recommends a polar arc equal to at least twice the slot pitch. On the other hand the arc of the interpole must not occupy too great a percentage of the interpolar gap. It usually takes up approximately one-third of the interpolar arc.

Given the polar arc, the length of the pole shoe is determined by the area required to carry the necessary auxiliary

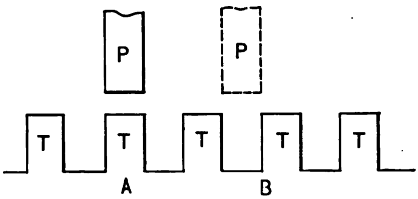


Fig. 12.

pole flux. It is best to reduce the axial length as much as possible in order to keep down the leakage. In practice it ranges from 60 to 80 per cent of the axial length of the armature core. The air-gap density should be about the same at approximately 50 per cent overload as it is under the main poles at normal load. If the pole cores were almost saturated at normal load, a sufficiently strong commutating field would not be forthcoming on heavy overloads, since the strength of the auxiliary field would not increase anywhere near in proportion to the load. The pole core density should therefore not come up to that of the main field except on approximately 50 per cent overload.

The total number of auxiliary field ampere turns is equal to the armature ampere turns per pole plus the ampere turns necessary to send the required flux through the auxiliary magnetic circuit. In practice it is customary to allow about 50 per cent more ampere turns on the auxiliary field winding than there are armature ampere turns per pole, and then to experimentally adjust the auxiliary field by means of an adjustable resistance in multiple to give the best commutating results.

For well-designed machines running at a moderate and fairly constant speed there is nothing to be gained by using inter-poles as they add considerably to the cost of the machine and at the same time tend to reduce the efficiency because of the additional losses.

(T) Efficiency

Assume the windage and bearing friction losses and calculate the efficiency at various loads. These losses are very difficult to pre-determine with even a reasonable degree of accuracy. They often vary widely even in similar machines of the same make, type and capacity, because of the variation in bearing friction. For high-speed belt-driven machines ranging in speed from 1200 r.p.m. to 1800 r.p.m., and from 20 to 300 kw., these losses should range from 1.5 per cent of the output for the larger machines to 3 per cent in the smaller sizes. For low speed belted machines running at from 300 to 600 r.p.m., and ranging in capacity from 20 kw. to 500 kw., they should range from 1 per cent for the larger sizes to 2 per cent for the smaller. For direct connected generators this figure should vary from $\frac{1}{3}$ of 1 per cent to 1 per cent, depending upon the size, speed and alignment.

Tabulate the losses and efficiency as follows:

Load in per cent	Arm $I\ R$.	Series I^2R.	Shunt I^2R.	Core Loss.	Brush Friction.	Windage and Bearing Friction.	Total Losses.	Efficiency in per cent.
0								
25								
50								
75								
100								
125								
150								

From the data in the above table for armature I^2R and core loss the temperature rise at different loads may be found.

From the above data curves of efficiency and temperature rise for continuous operation at the different loads may be plotted, and the variable and constant losses shown by curves.

The mechanical details are to be worked out on the drawing board as the work proceeds.

Fig. 13.—Spherical Type Direct-current Dynamo. (Electric Machinery Co.)

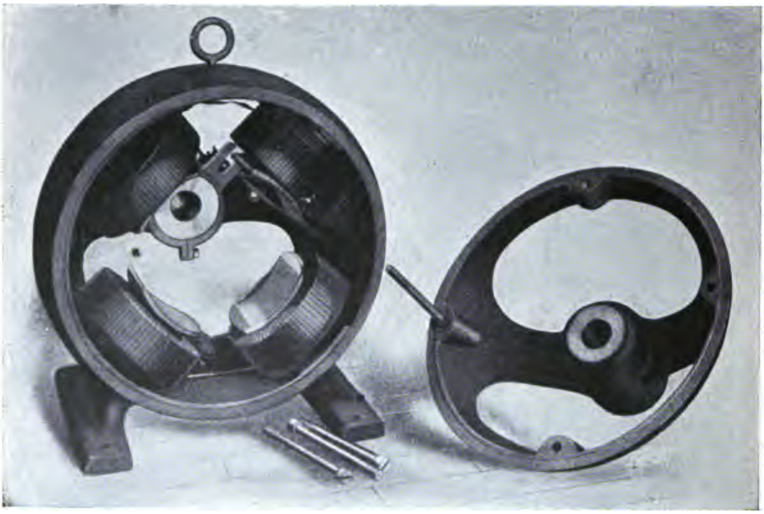


Fig. 14.—Frame and Field Coils of a Direct-current Dynamo. (Electric Machinery Co.)

Fig. 15.—Brush-holder of Large Direct-current Dynamo. (Electric Machinery Co.)

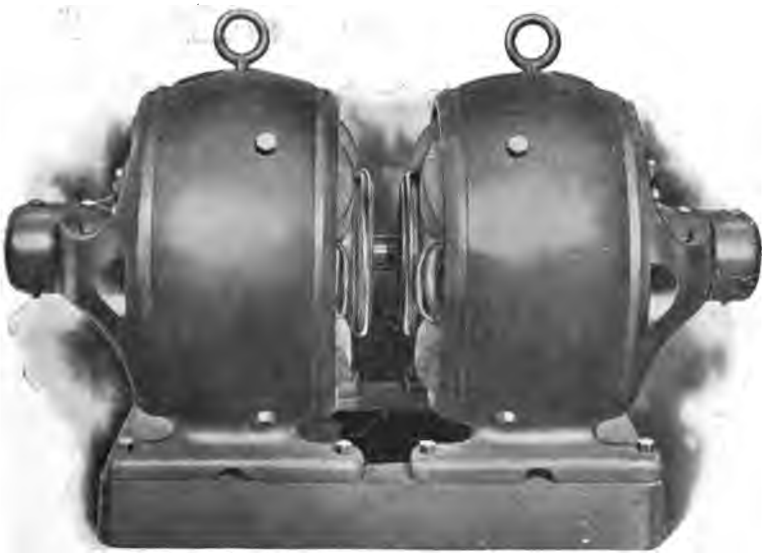


Fig. 16.—Three-wire Balancer Set. (Electric Machinery Co.)

Fig. 17.—300 K.W. 90 Revolutions per Minute at Donaldson's Glass Block, Minneapolis. (Electric Machinery Co.)

The machine shown in Fig. 17 is the one for which the calculations are given in Chapter III. At the time this machine was designed the largest mill in the shop had a clearance of 135 inches. The first calculations gave an over-all diameter of 147 inches. The diameter of the field ring was therefore reduced accordingly. This illustrates very nicely one of the many reasons why the student has before him a very different problem than the commercial designer, because of the absence of factory limitations.

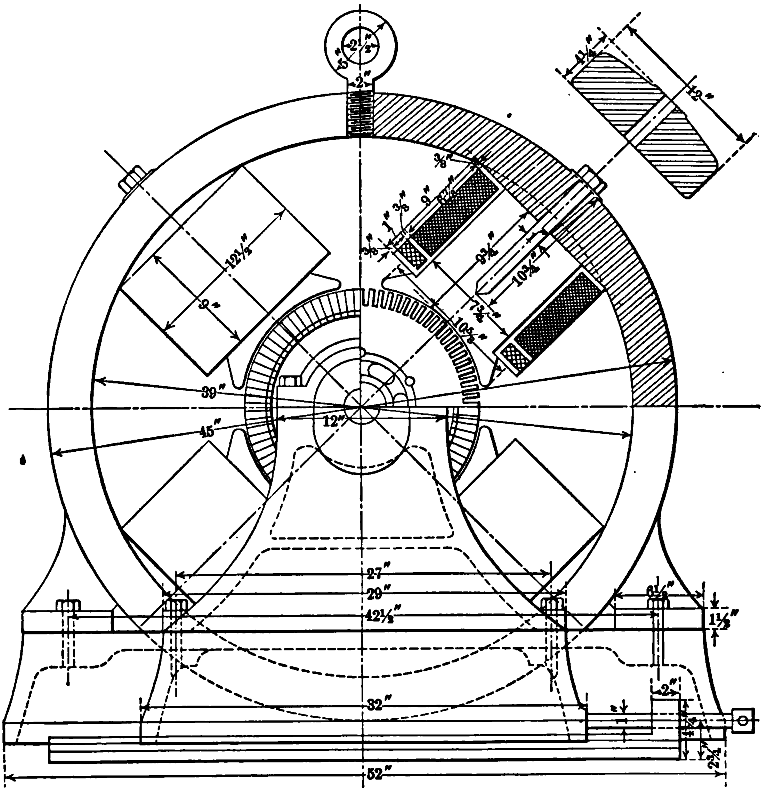
CHAPTER II

ILLUSTRATIVE DESIGNS

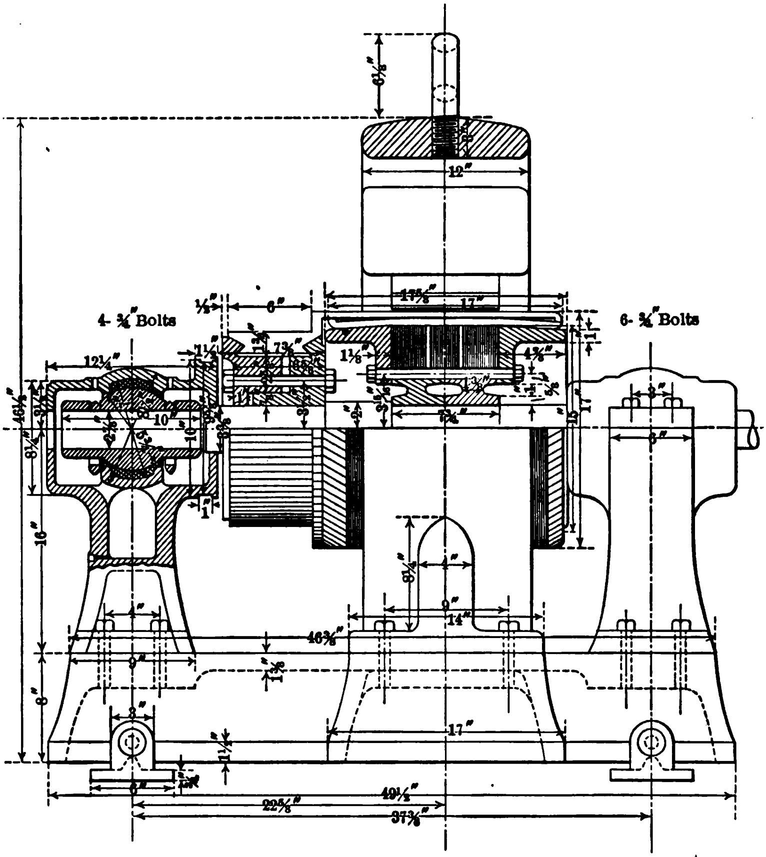
THE following illustrations are made from some dynamo designs worked out by senior students in electrical engineering under the guidance of the author and applying the method of design laid down in Chapter I.

DESIGN No. 1.

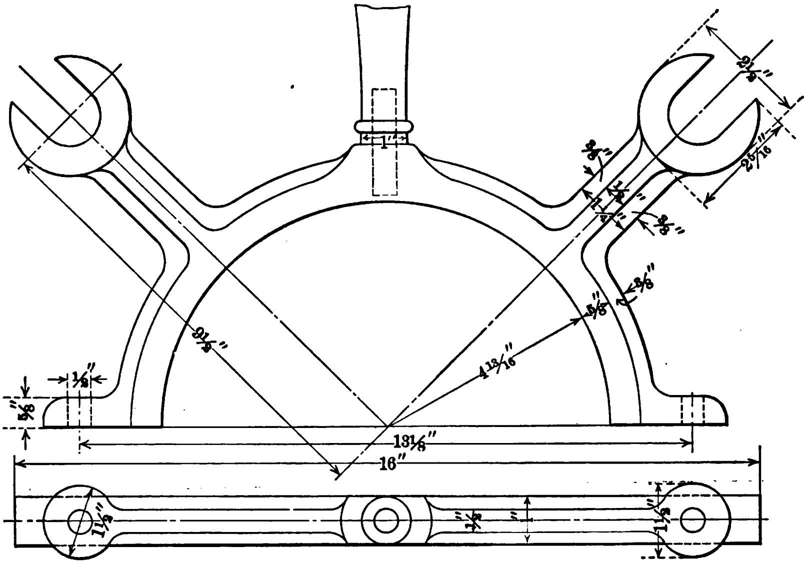
40-Killowatt Direct-current Generator. 220-Volts, No-load and Full-load. 186.2 Amperes. 600 r.p.m.



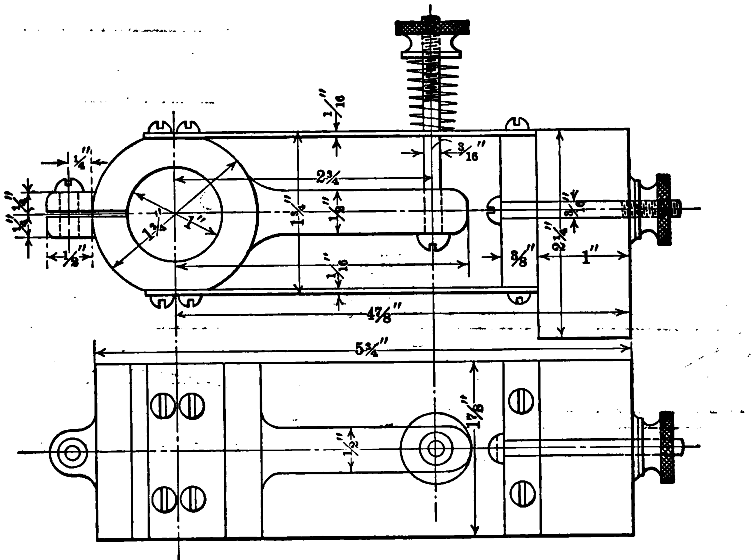
DESIGN No. 1.—*Continued.*



DESIGN No. 1.—*Continued.*

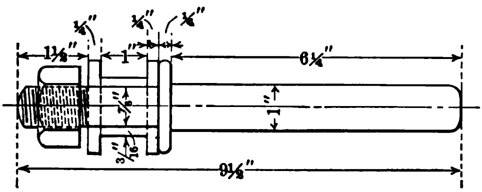


BRUSH YOKE

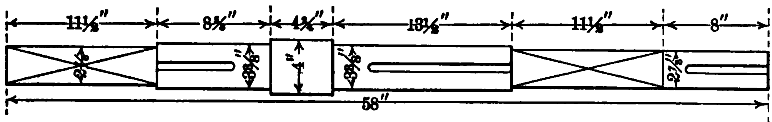


BRUSH HOLDER

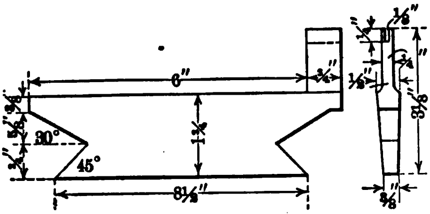
DESIGN No. 1.—*Continued.*



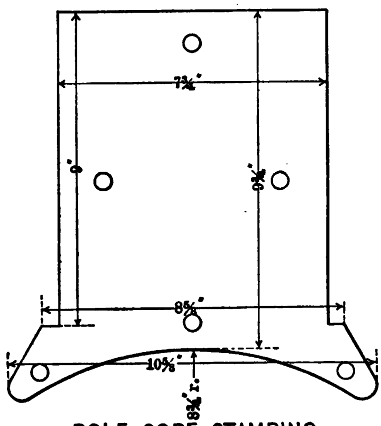
BRUSH YOKE STUD



SHAFT



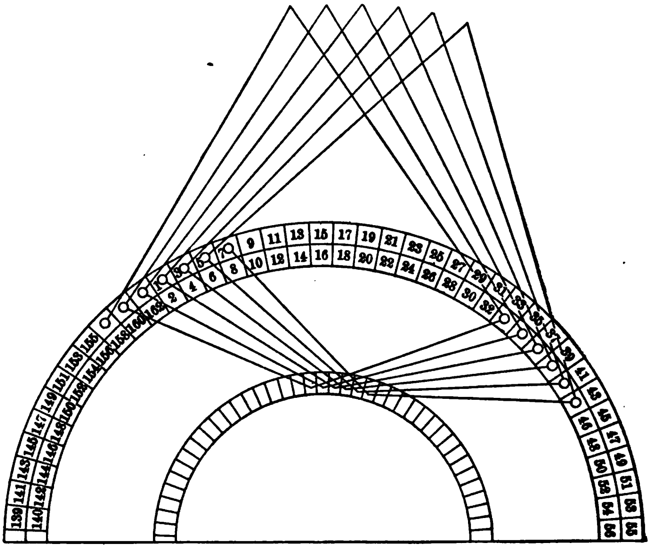
COMMUTATOR BAR



POLE CORE STAMPING

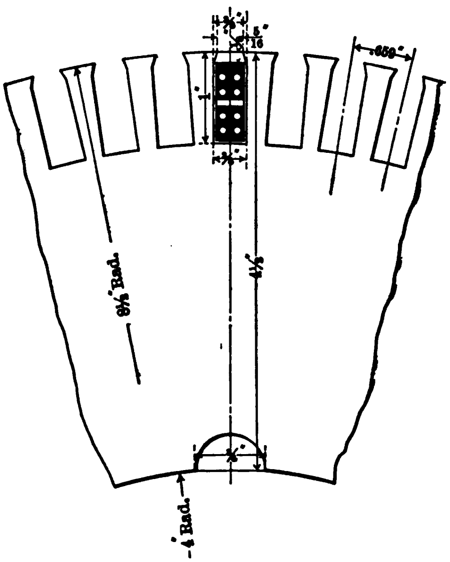
.02 Inch Steel

DESIGN No. 1.—*Continued.*



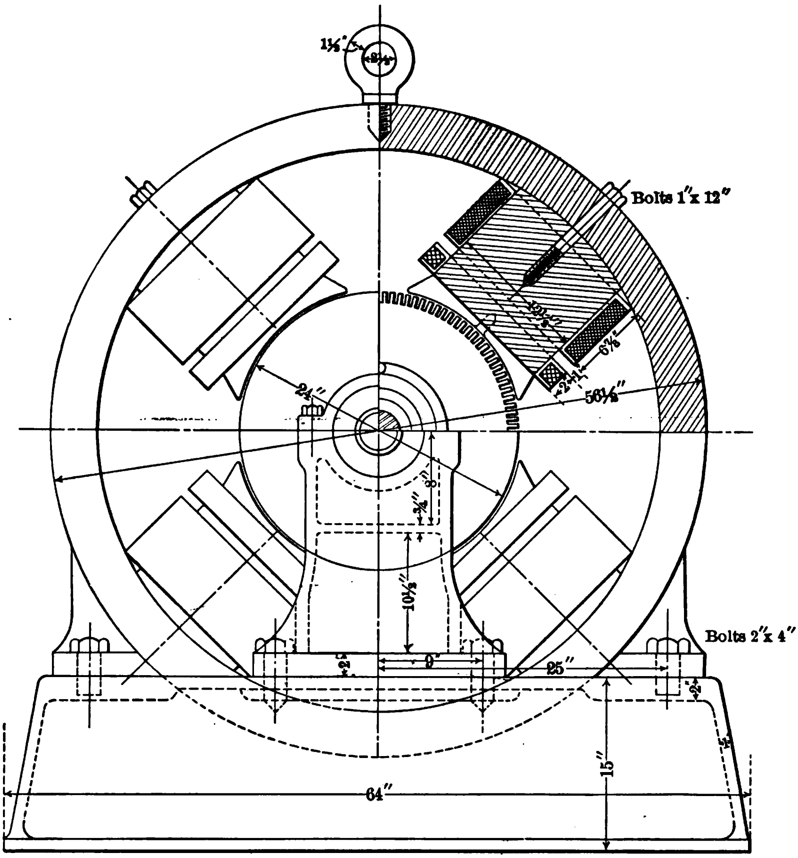
WIRING DIAGRAM

ARMATURE CORE STAMPING
81 Slots .02 Inch Steel

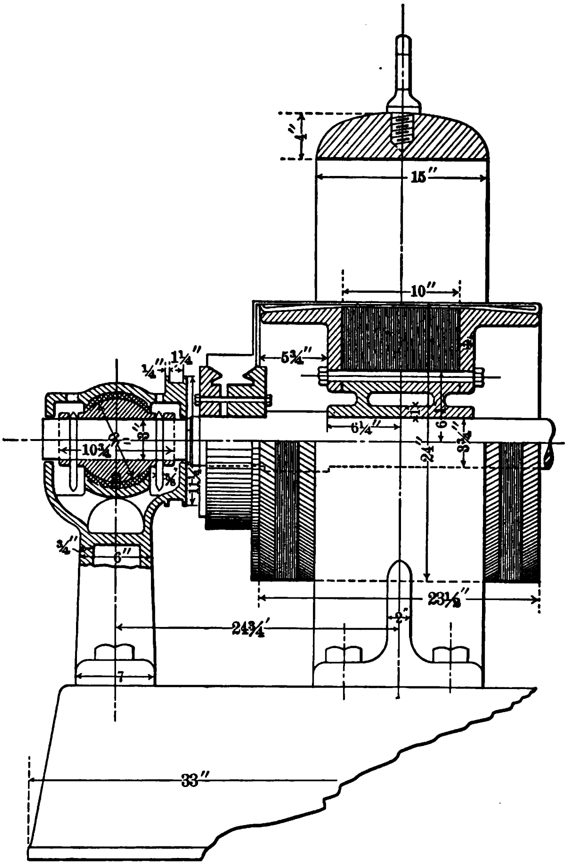


DESIGN No. 2.

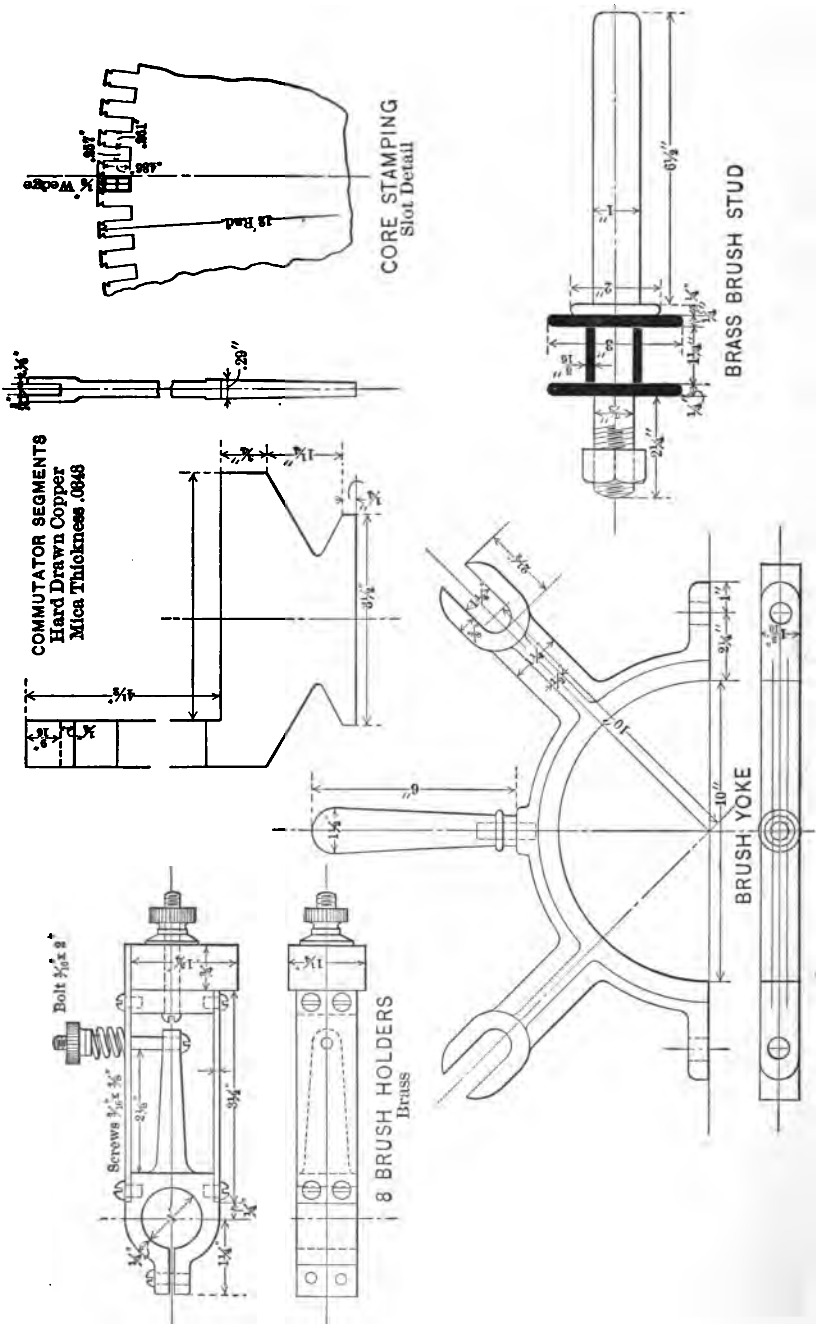
60-Kilowatt Direct-current Generator. 500-550 Volts. 800 r.p.m.



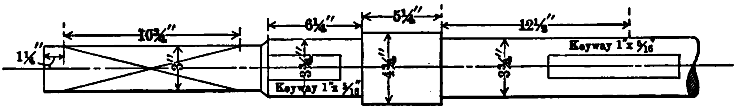
DESIGN No. 2.—*Continued.*



DESIGN No. 2.—*Continued.*



DESIGN No. 2.—*Continued.*



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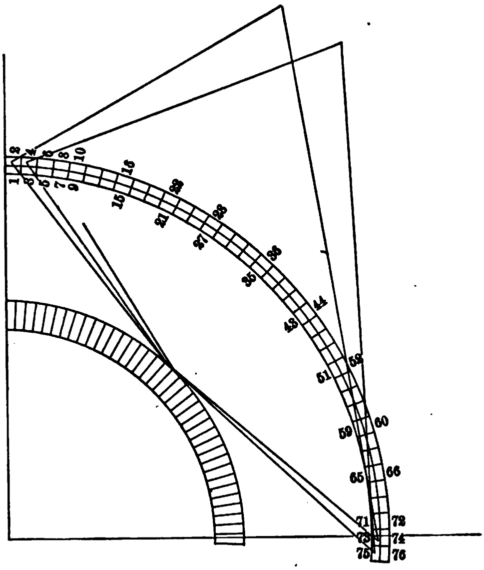
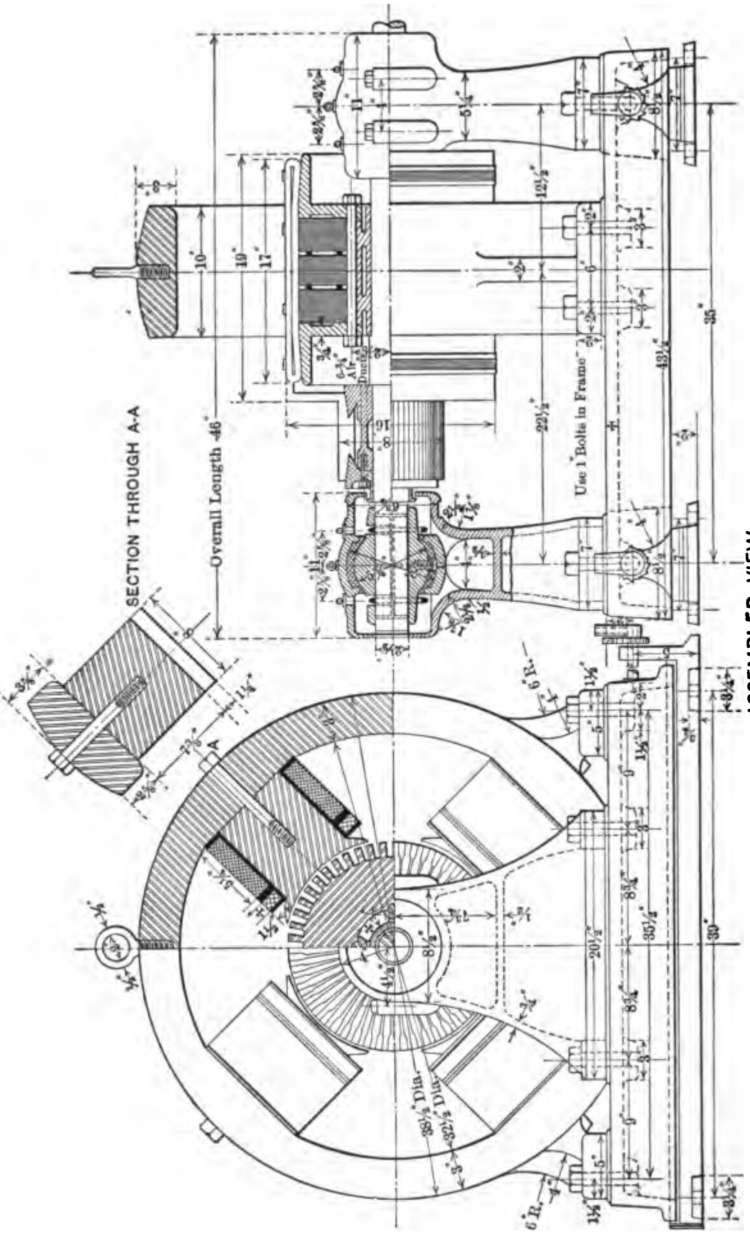


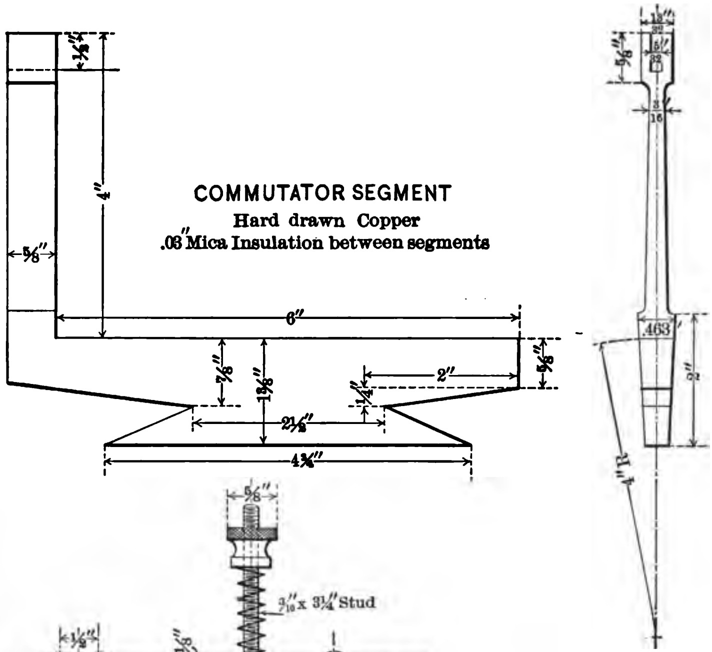
WINDING DIAGRAM

Simplex Lap **Front Pitch - 71**

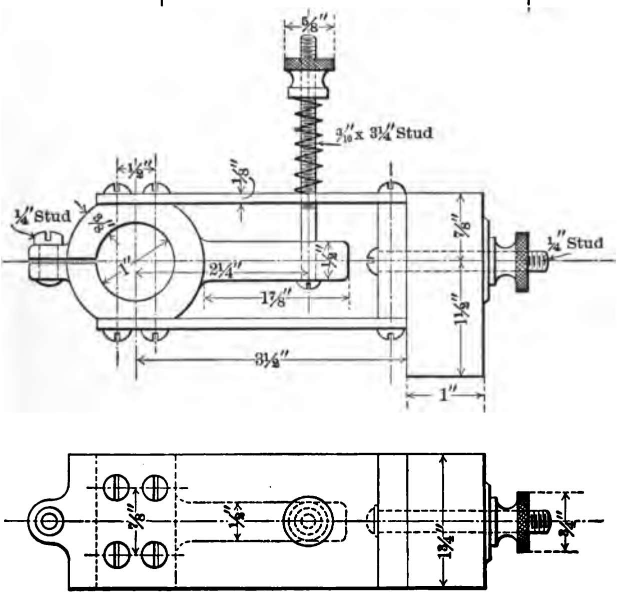


DESIGN No. 3.—30-Kilowatt Direct-current Generator. 125 Volts. 600 r.p.m.

DESIGN No. 3.—*Continued.*

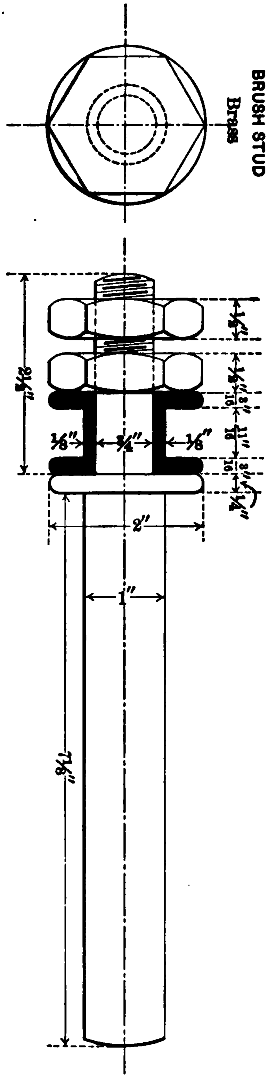


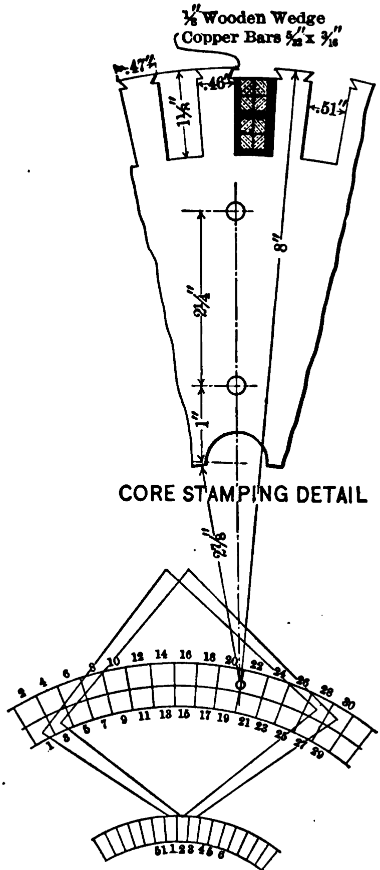
COMMUTATOR SEGMENT
Hard drawn Copper
.03" Mica Insulation between segments



BRASS BRUSH HOLDER
Carbon Brush

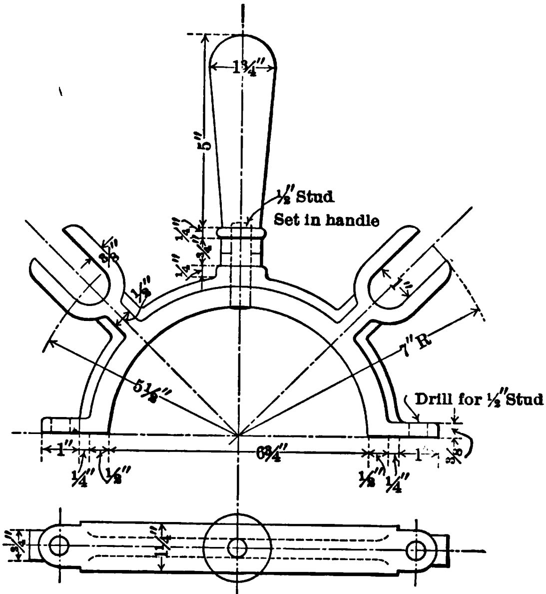
DESIGN No. 3.—*Continued.*



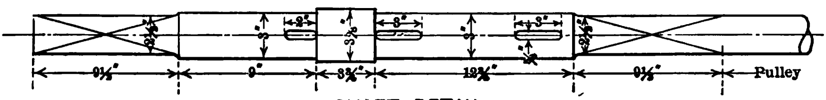


WINDING DIAGRAM
Lap winding-2 coils per Slot-4 turns per Coil

DESIGN No. 3.—*Continued.*



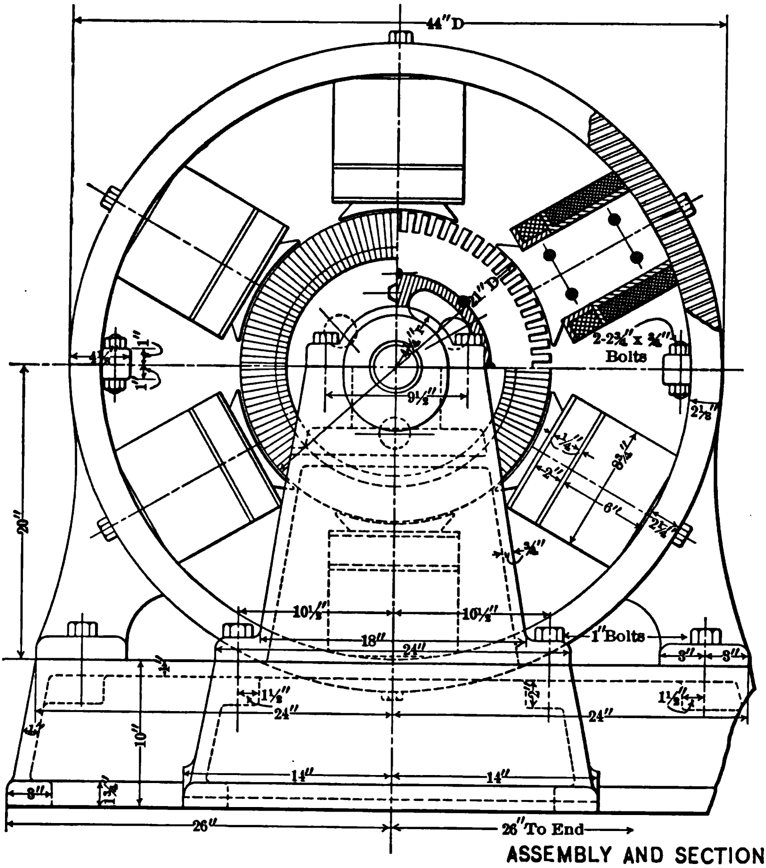
BRUSH YOKE
Handle on one



SHAFT DETAIL
Keyway for ⅛" x ⅝" Sunk Keys

DESIGN No. 4.

50-Kilowatt Direct-current Generator. 220-250 Volts. 550 r.p.m.



ASSEMBLY AND SECTIONS

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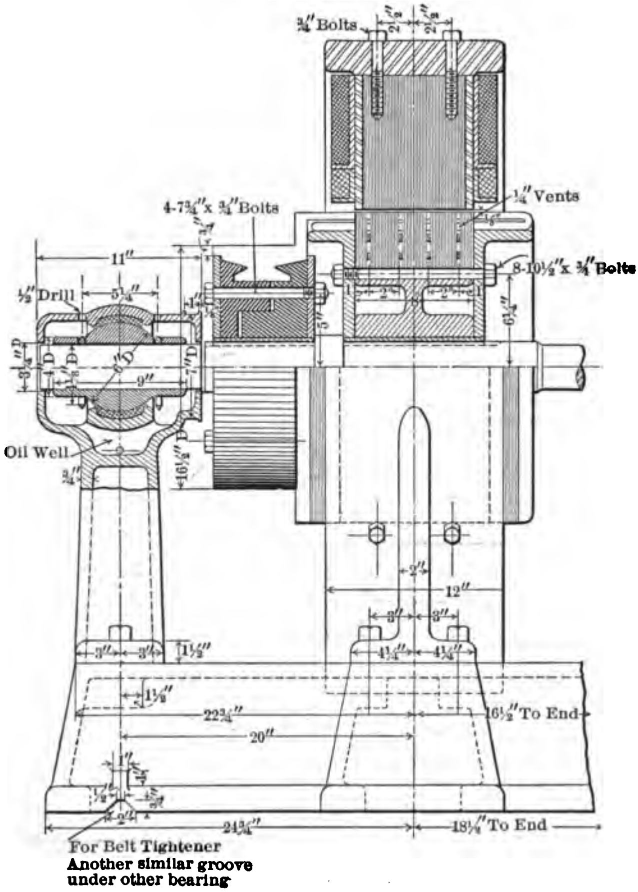
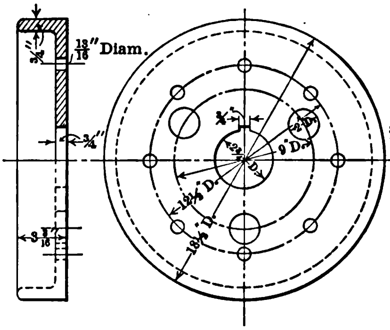
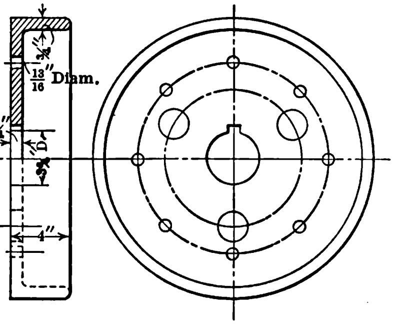


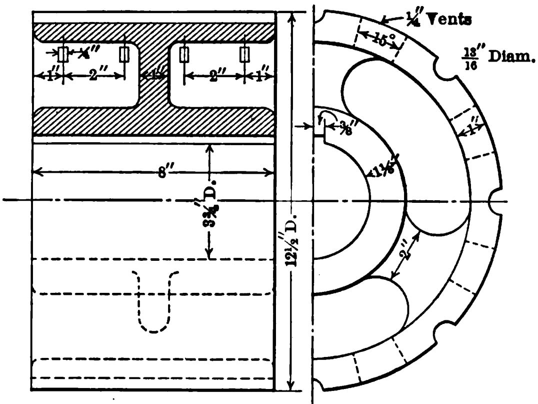
DESIGN No. 4.—*Continued.*



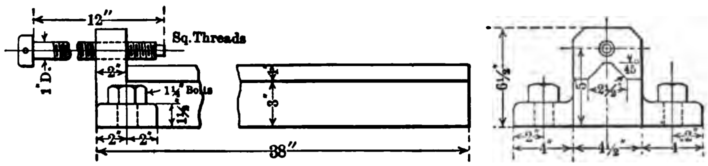
ARMATURE END PLATE
COMMUTATOR END-CAST IRON



ARMATURE END PLATE
PULLEY END-CAST IRON

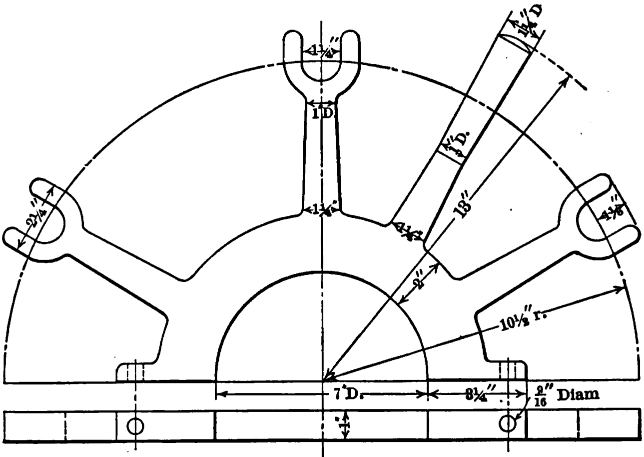


ARMATURE SPIDER
Cast Iron

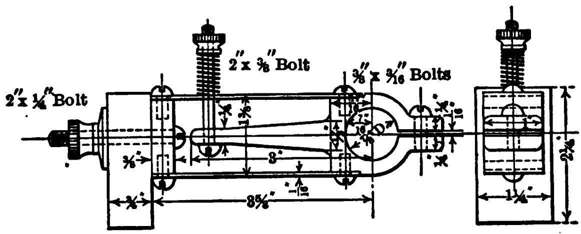


BELT TIGHTENER-CAST IRON

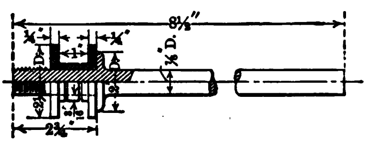
DESIGN No. 4.—*Continued.*



BRUSH YOKE-UPPER HALF-CAST IRON
LOWER HALF SAME WITHOUT HANDLE

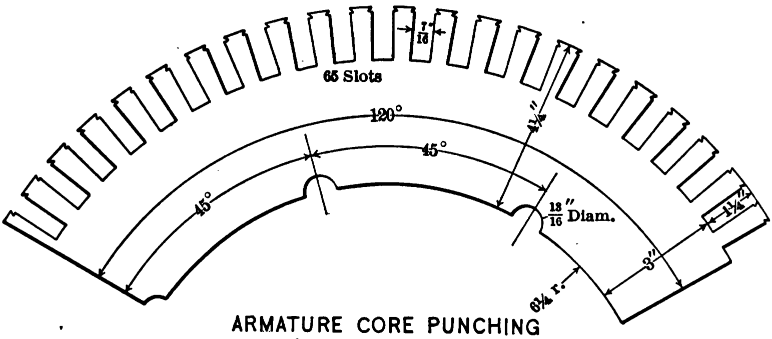


BRUSH HOLDER
Brass

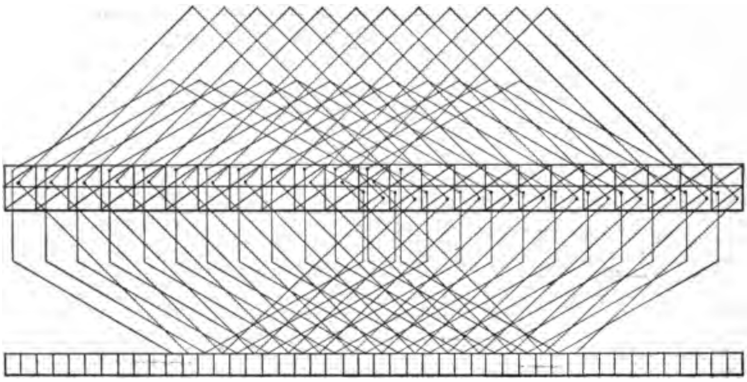


BRUSH HOLDER STUD
Brass

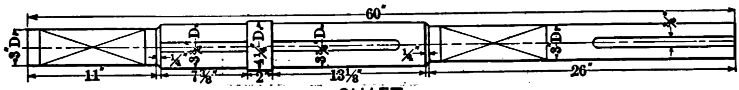
DESIGN No. 4.—*Continued.*



ARMATURE CORE PUNCHING
16 Mil. Sheet Steel

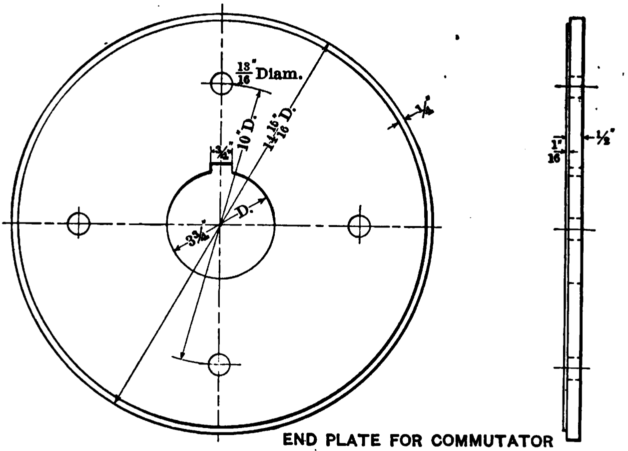


WINDING DIAGRAM-65 DOUBLE COILS
FRONT PITCH-21 BACK PITCH-23

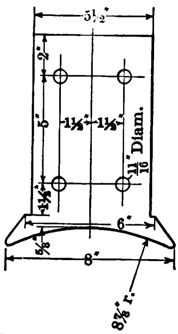


SHAFT
Machine Steel

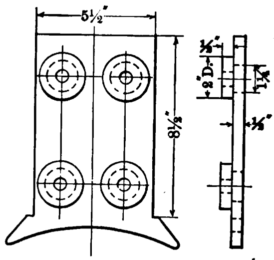
DESIGN No. 4.—*Continued.*



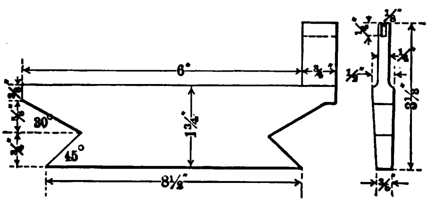
END PLATE FOR COMMUTATOR
Cast Iron



POLE CORE PUNCHING
6 Mil. Sheet Steel

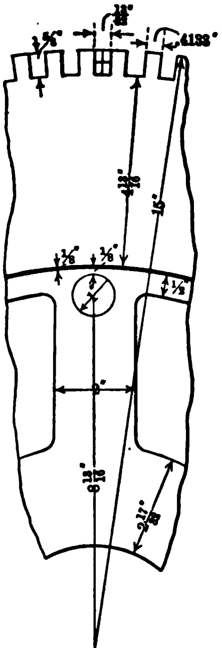


END PLATE FOR POLE CORE
Cast Steel

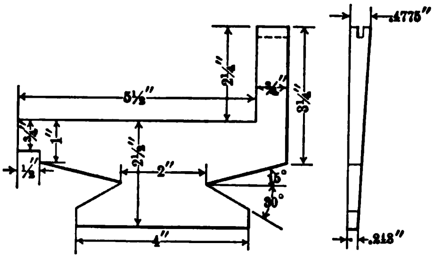


COMMUTATOR BAR

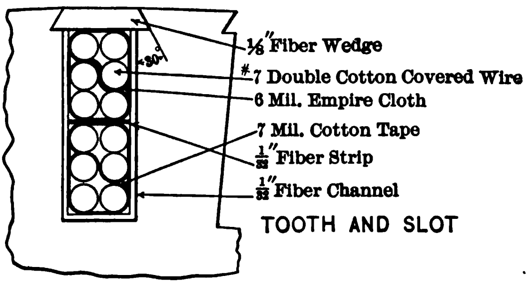
DESIGN No. 4.—*Continued.*



CORE STAMPING DETAIL



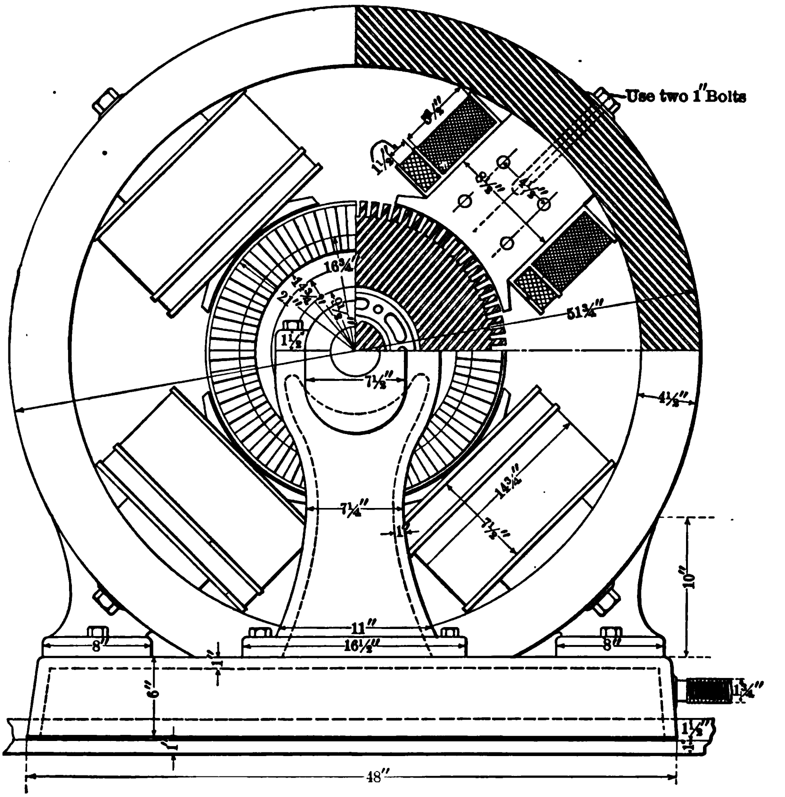
COMMUTATOR BAR
Copper

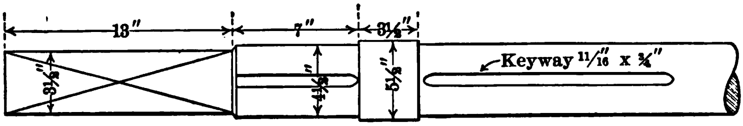


TOOTH AND SLOT

DESIGN No. 5.

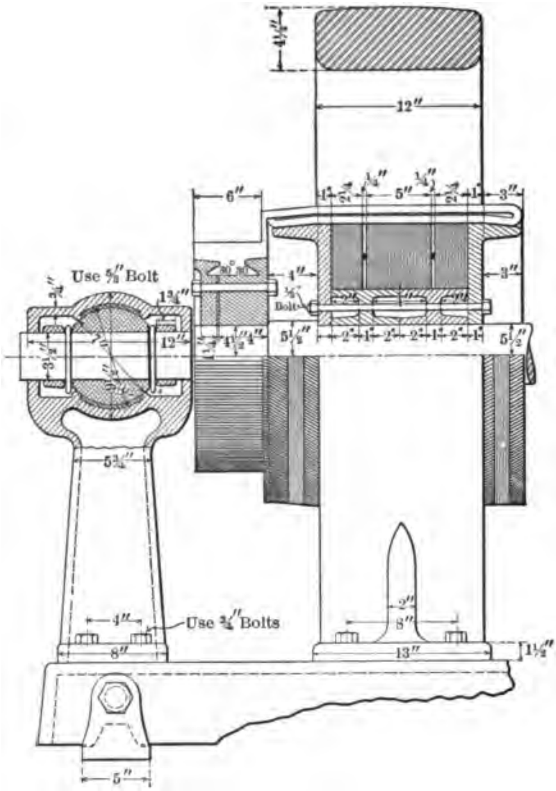
75-Kilowatt Direct-current Generator. 250 Volts. 500 r.p.m.

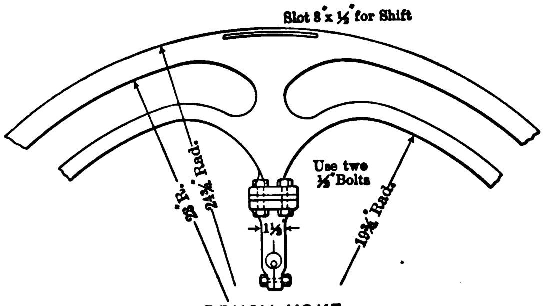




MACHINE STEEL SHAFT

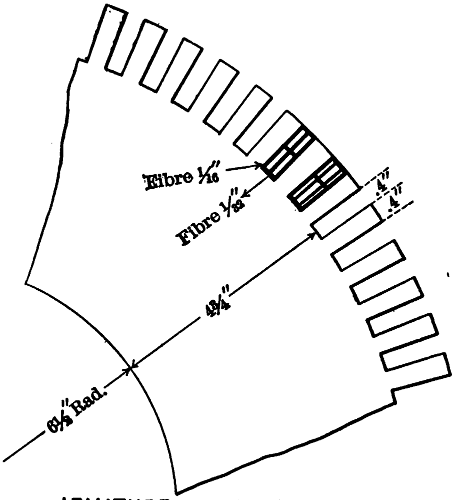
DESIGN No. 5—*Continued.*



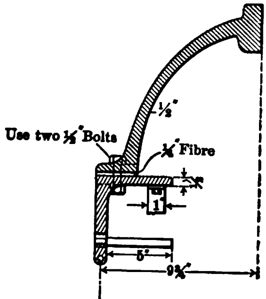


BRUSH YOKE

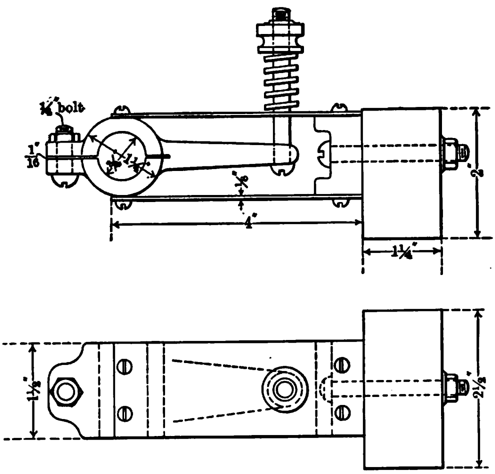
DESIGN No. 5.—*Continued.*



ARMATURE CORE PUNCHING
Sheet Steel .02" thick

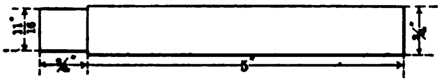


BRUSH YOKE

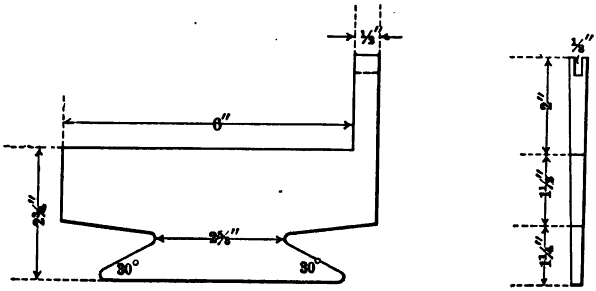


BRUSH HOLDER AND BRUSH

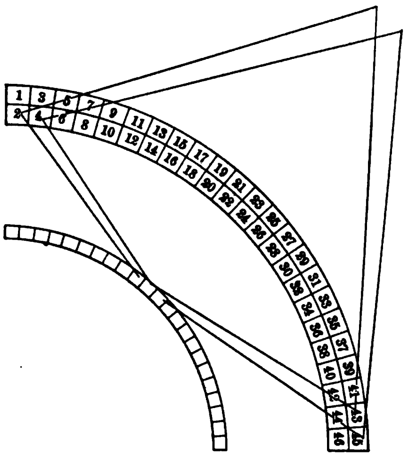
DESIGN No. 5.—*Continued.*



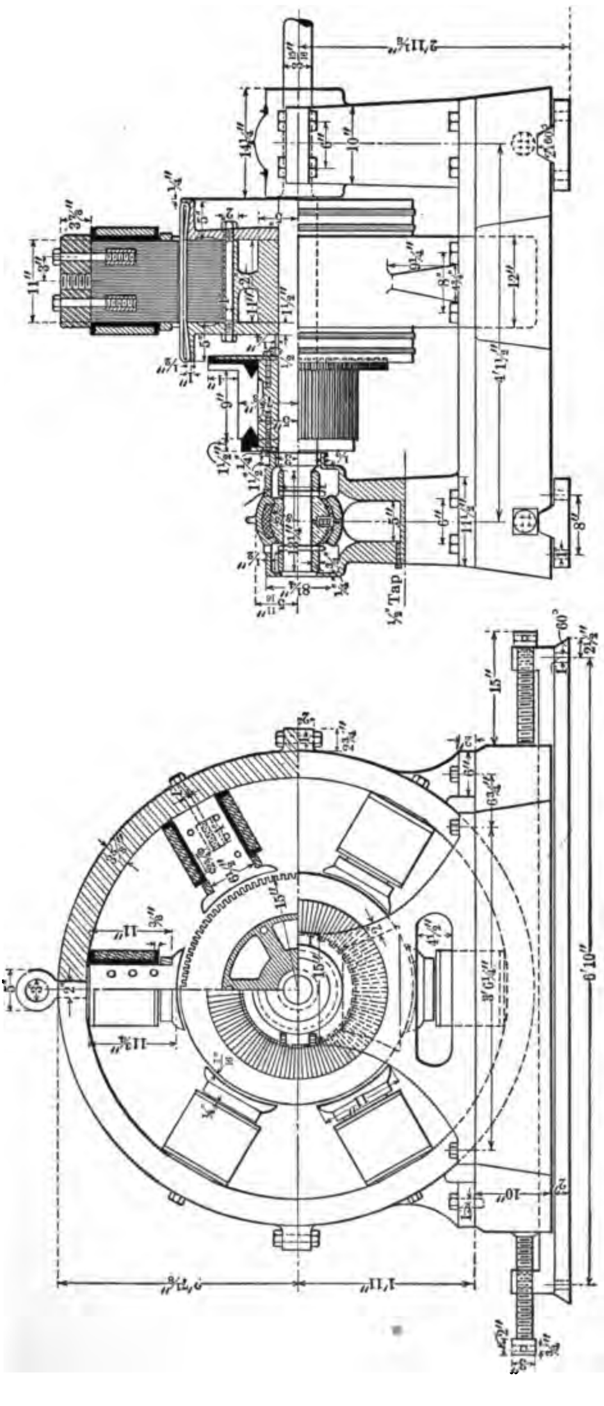
BRUSH HOLDER PIN



COMMUTATOR BAR
Hardened Copper

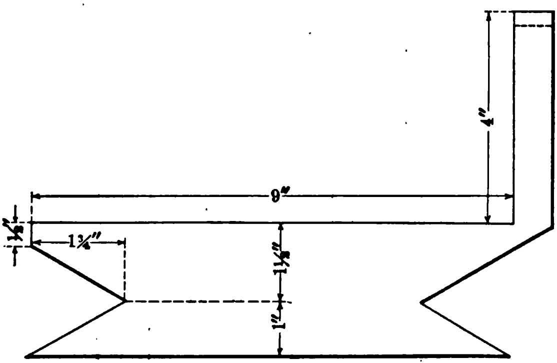


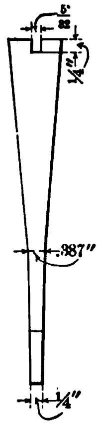
WINDING DIAGRAM
85 Coils 6 Inductors per Coil
Front Pitch 41 Back Pitch 39



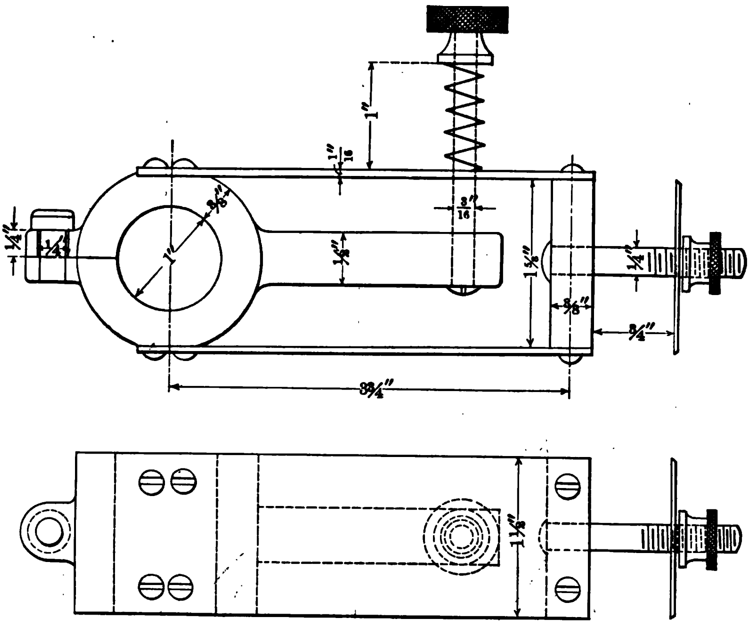
DESIGN No. 6.—100-Kilowatt Direct-current Generator. 230 Volts. 500 r.p.m.

DESIGN No. 6.—*Continued.*



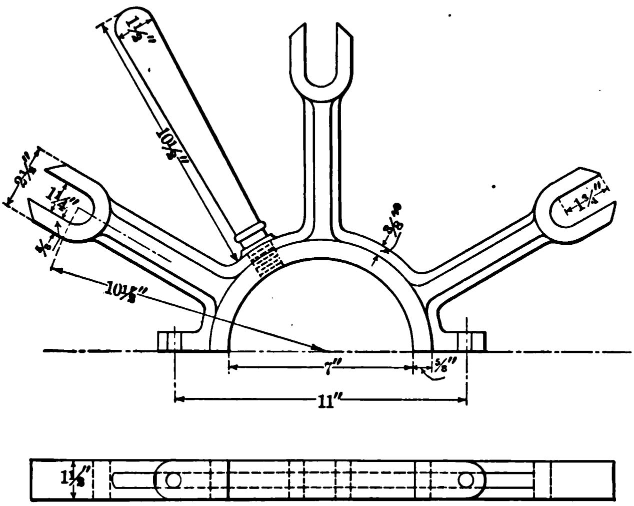


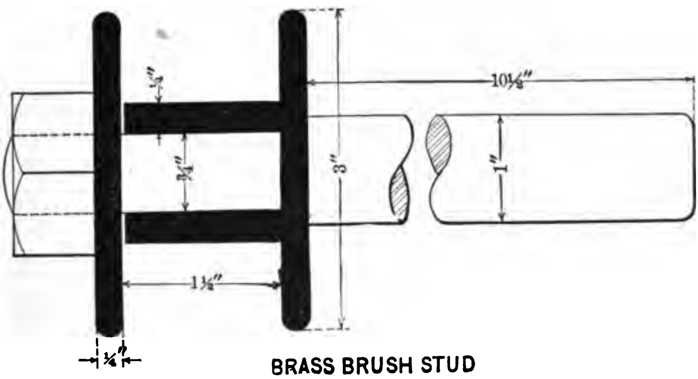
COMMUTATOR SEGMENT
Hard drawn Copper
.03" Insulation between Segments



BRASS BRUSH HOLDER
Carbon Brush

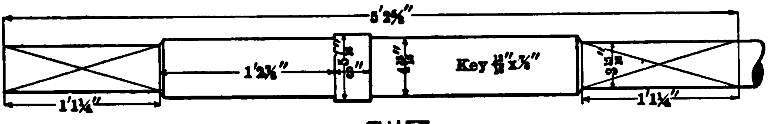
DESIGN No. 6.—*Continued.*



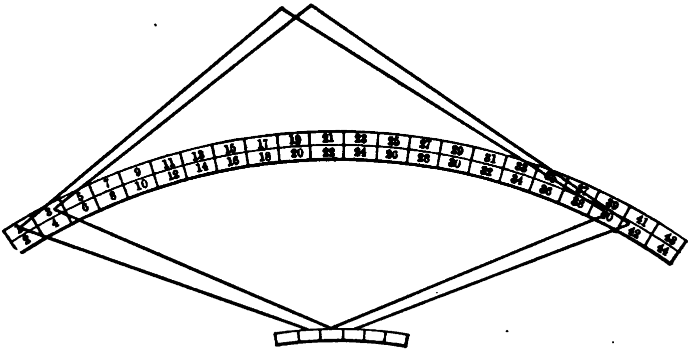


BRASS BRUSH STUD

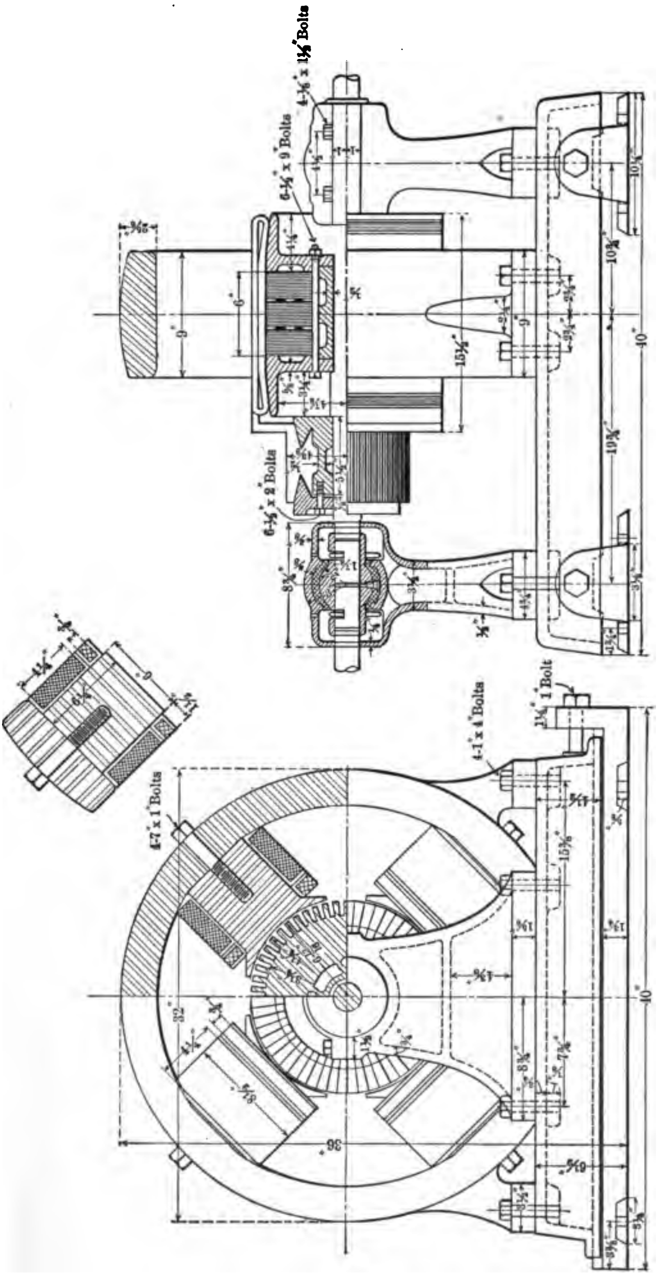
DESIGN No. 6.—*Continued.*



SHAFT

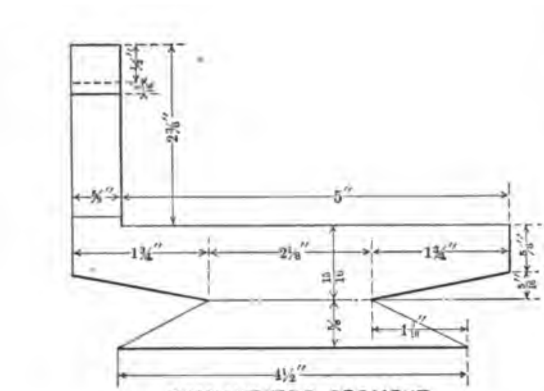


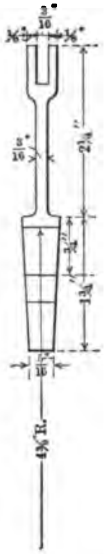
WINDING DIAGRAM
Lap Winding 2 Coils per Slot
2 Turns per Coil



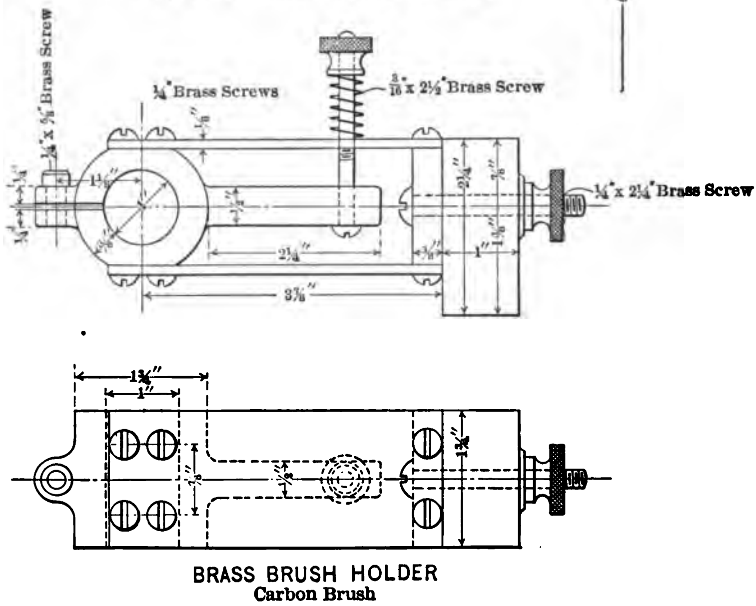
DESIGN No. 7.—20-Kilowatt Direct-current Generator. 130 Volt. 800 r.p.m.

DESIGN No. 7.—*Continued.*



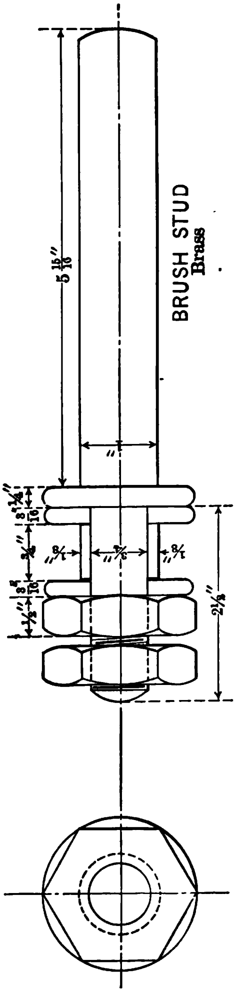


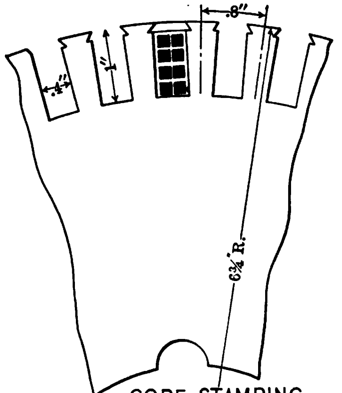
COMMUTATOR SEGMENT
Hard drawn Copper
.04 Mica Insulation Between Segments



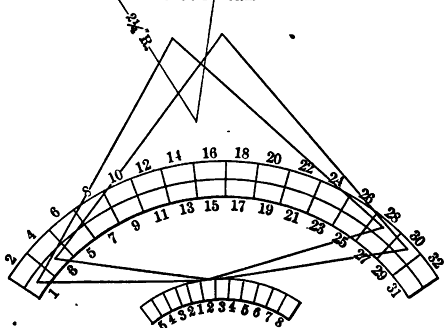
BRASS BRUSH HOLDER
Carbon Brush

DESIGN No. 7.—*Continued.*



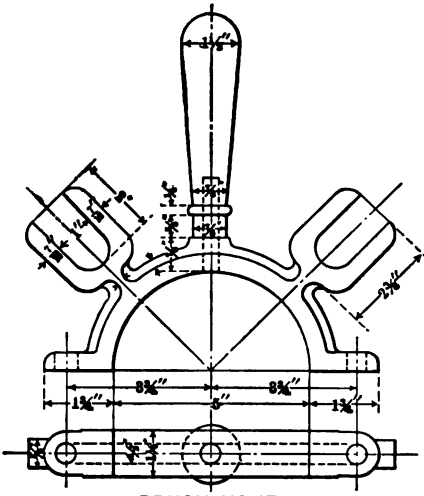


CORE STAMPING
Slot Detail

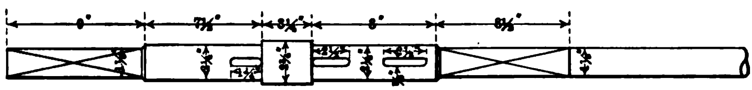


WINDING DIAGRAM
Lap Winding 2 Coils per Slot 2 Turns per Coil

DESIGN No. 7.—*Continued.*



BRUSH YOKE



Note:- Keyways for ⅝"x ½"Sunk Keys DETAIL OF SHAFT

CHAPTER III

DESIGN OF A 300-KILOWATT 90 R.P.M., 125-VOLT DIRECT-CURRENT GENERATOR

MR. TRUMAN HIBBARD, chief designer for the Electric Machinery Co., Minneapolis, Minn., very kindly supplied the author with the following set of calculations. The machine, for which the calculations follow, is in operation in L. S. Donaldson's Glass Block, Minneapolis, Minn., and may be seen at any time.

A 300-KW., 125-volt dynamo compounded 5 per cent, to be driven by a Corliss engine running at from 90–100 r.p.m.

$DL = C$ KW., $C = 3$ for this case (Steinmetz) making $D = 5L$;

$$D^2 = (5)(900);$$

$$D = \sqrt{4500} = 67 \text{ inches};$$

$$D^2L = \frac{36 \times 10^4 (1.5\sqrt{\text{KW.}})^2}{\text{r.p.m.}}. \qquad \text{(Press)}$$

$$D^2L = \frac{36 \times 10^4 (1.5 + \sqrt{300})^2}{90}.$$

Making $D = 5L$ and solving we get,

$$D^3 = 7{,}080{,}000 = 192 \text{ cm.} = 76 \text{ inches};$$

$$D^2L = \frac{\text{KW.}}{.064 + \text{r.p.m.}}. \qquad \text{(Thompson)}$$

Solving the above for D when $D = 5L$ we get,

$D = 76.6$ inches; $C = 7000$ to $35{,}000$ assuming $8{,}000$;

$$DL = \frac{\text{KW.} \times C}{\text{feet per min.}};$$

$$D^2 = \frac{5 \times 300 \times 800}{\frac{\pi \times D}{12} \times 90};$$

$$D = \sqrt[3]{510{,}000} = 79.9 \text{ inches.}$$

Average the four values just obtained.

$$\begin{array}{r l} & 67 \\ & 76 \\ & 76.6 \\ & \underline{79.9} \\ 4) & \underline{299.5} \\ & 74.9, \text{ say 75 inch diam.} \end{array}$$

$$L = \frac{D}{5} = 15 \text{ ins.}$$

Assuming that we are to use a round pole the pole will be 15 ins. in diameter $=177$ sq.in.

$$B_p=59{,}000 \text{ (assumed)},$$

$$\phi=177\times 95{,}000=16{,}800{,}000.$$

Assume leakage coefficient $=1.2=V$.

$$\text{Working flux}=\frac{16{,}800{,}000}{1.2}=14{,}000{,}000.$$

By Kapp's formula,

$$\phi=\frac{65{,}000\sqrt{\text{KW.}}\times 2000\times\sqrt{\dfrac{1000}{\text{r.p.m.}}}}{5}=15{,}000{,}000.$$

This checks very well with the value 14,000,000.
Copper loss in armature assumed 2.45 per cent.

$$.0245\times 300{,}000=7350 \text{ watts};$$

Current $=2400$ amperes;

$$e=\frac{7350}{2400}=3.06, \text{ say } 3;$$

$$E=125+3=128 \text{ volts};$$

$$E=\frac{S\phi V}{10^8\times 60};$$

$$S=\frac{(E)(10^8)(60)}{(\phi)(\text{r.p.m.})};$$

$$S=\frac{(128)(10^8)(60)}{(14{,}000{,}000)(90)}=610, \text{ say } 600.$$

To get the number of poles,

$$2^{\frac{p-4}{2}}=\frac{D^2L}{150{,}000}. \qquad \text{(Press)}$$

Substituting in the above formula we get 10 poles.

$$\frac{600}{2}=300 \text{ slots (min. number)},$$

$$300=\text{max. number com. bars.}$$

Check. Thompson says amp. $\times$ cond. per pole should not exceed 14,000. Here $\frac{2400}{10}\times 30\times 2=14{,}400$, a little high.

Slot pitch $=\frac{75\times\pi}{300}=.787$ in.; assuming an approximate slot width $=\frac{1}{2}$ slot pitch we get the width of slot to be .393 in., say .4 in.

Assuming slot depth to be roughly four times its width we get a slot depth of $4\times .4=1.6$ ins.

Then the active belt would be $\pi(D-a)\times a\times L$, where a = depth or slot $=\pi(75-1.6)\times 1.6\times 15=5500$ cu. ins.

Thompson says watts generated divided by cubic inches in active belt should vary from 40 to 120.

In this case,

$$\frac{300000}{5500}=55.$$

Length of Pole Core. It must be sufficiently long to allow for radiation and the accommodation of the windings. Assume a shunt loss of 1.4 per cent.

$$300000\times .014=4200 \text{ watts},$$

$$\frac{4200}{10}=420 \text{ watts per pole.}$$

Allowing .7 watt per square inch pole surface,

$$\frac{420}{.7}=600 \text{ sq.ins.}$$

Hence,

$$L=\frac{600}{\pi \times 15}=12.7 \text{ ins. for shunt only.}$$

Add, say, 60 per cent for compound winding and we get $12.7 \times 1.5 = 19$ ins. Roughly,

$$\text{ring thickness} = \tfrac{1}{3} \text{ pole diameter} = 5 \text{ ins.}$$

$$\text{Ring diam.} = 75 + (19+5)2 = 123 \text{ ins.}$$

Adding say 12 ins. to the ring radius for each one of the feet the frame is to rest upon, we obtain,

$$\text{Ring diam. max.} = 123 + 24 = 147 \text{ ins.}$$

The largest mill in the shop has a clearance of 135 ins., hence the diameter must be reduced.

Taking a polar embrace of 72 per cent and making the pole core 15 ins. in diameter, we find the min. diameter of the armature to be 66 ins.

$$\text{Pole shoe} = \frac{.72 \times 66 \times \pi}{10} = 15.2 \text{ ins.;}$$

$$\text{Air-gap (max.)} = \frac{D}{50+D} = \frac{66}{66+50} = .57 \text{ in.}$$

$$\text{Air-gap (min.)} = \frac{D}{200+2D} = \frac{66}{332} = .2;$$

Assumed air-gap $= \frac{1}{2}$ inch;

$$\text{Bore} = 66 + (2 \times \tfrac{1}{2}) = 67 \text{ ins.};$$

$$\text{Pole pitch} = \frac{67 \times \pi}{10} = 21 \text{ ins.}$$

Compromising between factory limitations and ideal requirements we will make the outside of the ring as large as the mill will swing.

Allowing 12 ins. for each foot this leaves $135 - 24 = 111$, say 110 ins. for the outside diameter of the ring.

Fixing thickness of the pole shoe at $1\frac{1}{4}$ ins. we get the diameter at the face of the field coils to be $66 + 2(\frac{1}{2}) + 2(1\frac{1}{4}) = 69\frac{1}{2}$ ins.

$$\text{Space for field coils} = \frac{69\frac{1}{2} \times \pi}{10} = 22.$$

For ventilation reasons the field coils should not come closer than 2 ins. apart. From experience, etc., the shunt winding is assumed to be 3 ins. deep. This gives space for core,

$$22 - (2 \times 2) - (2 \times 3) = 12 \text{ ins.}$$

With a leakage coefficient of 1.18 we get a total flux of 18,000,000, approximately.

Using 100,000 lines of force per square inch and a core 12 ins. thick it is necessary to add a rectangle 6 ins. $\times$ 12 ins. in the center of the 12-in. round pole.

$$\text{Area} = \frac{\pi (12)^2}{4} + 6 \times 12 = 185 \text{ sq.in.}$$

$185 \times 100000 = 18500000$ lines of force $= \phi$;

$\phi_a =$ Flux in armature $= \dfrac{18500000}{1.18} = 15700000$;

$$S = \frac{E \times 10^8 \times 60}{Na \times \text{r.p.m.}} = \frac{128 \times 10^8 \times 60}{15700000 \times 90} = 545;$$

$S = 545$, say 540.

270 slots and 270 ccm. bars.

$$\text{Volts per bar} = \frac{125}{27} = 4.53 \text{ (very low).}$$

Again applying Thompson's check,

$$\frac{2400}{10} \times \frac{540}{10} = 12950,$$

which is a little below Thompson's maximum of 14,000.

$$\text{Slot pitch} = \frac{\pi \times 66}{270} = .77 \text{ in.}$$

$$\text{Width of slot approx. } \frac{.77}{2} = .38.$$

Magnetic Circuits.

72 per cent of $27 = 19\frac{1}{2} =$ number of teeth per pole.

Adding $1\frac{1}{2}$ teeth for fringing we get 21 teeth to carry the pole flux.

Length of Armature.

$$D^2L=\frac{36\times10^4\times(1.5+\sqrt{\text{KW.}})^2}{\text{r.p.m.}}\text{ in cm.};$$

$$L=\frac{36\times10^4\times(1.5+17.3)^2}{66\times2.45\times66\times2.45\times90}=54.6;$$

$$L=54.6\text{ cm.}=22.3\text{ ins.};$$

from

$$DL=3\text{ KW.},$$

$$L=\frac{3\times300}{66}=13.6;$$

from

$$D^2L=\frac{\text{KW.}}{.064\times\text{r.p.m.}},$$

$$L=\frac{300}{\frac{66}{12}\times\frac{66}{12}\times.064\times90}=1.72\text{ ft.},$$

$$L=1.72\text{ ft.}=20.7\text{ ins.};$$

from

$$DL=\frac{\text{KW.}\times8000}{\text{feet per min.}},$$

$$L=\frac{300\times8000}{66\times\pi\times5.5\times90}=23.3\text{ ins.}$$

Averaging,

$$\begin{array}{r} 23.3 \\ 20.7 \\ 22.3 \\ 13.6 \\ \hline 4\overline{)79.9} \\ 19.975,\text{ say, }20\text{ ins.} \end{array}$$

Assuming six $\frac{3}{8}$ vents in the core, the net length of iron in the teeth is $20-(6\times\frac{3}{8})=17\frac{3}{4}$ ins. Assuming 5 per cent of this insulation we have $17.75\times.95=16.85$ ins. Area of 21 teeth then would be $21\times16.85\times.372=131.5$ sq.ins.

$$\text{Flux density in teeth}=\frac{15700000}{131.5}=119500;$$

$$\text{Density in air-gap}=\frac{\phi a}{\text{area}};$$

$$\text{Air-gap area}=\frac{\text{area pole face}+\text{area teeth}\times1.25}{2};$$

$$\text{Area air-gap}=\frac{15\times20+(21\times.39\times20)1.25}{2}=251.25;$$

$$B\ (\text{air})=\frac{15700000}{251.25}=62500.$$

Field Ring.

$$\phi_f=18500000;$$

Working steel in ring at 90,000;

$$\text{Area}=\frac{18500000}{2\times90000}=102.5\text{ sq.in.}$$

Pole is 18 ins. long, ring should overhang so as to protect field coils, say, 2 ins. on each side.

Making it 22 ins. if the section is rectangular the thickness would be,

$$\frac{102.5}{22}=4.64\text{ ins.}$$

This section would not be stiff enough so make it 6 ins. deep and round off corners and back, giving $6\times22-$about $15=117$ sq.ins.

$$\text{Yoke density}=\frac{18500000}{2\times117}=79000=B_y$$

Armature Core Section. Using Ba in armature $=65{,}000$.

$$\text{Cross-section}=\frac{15700000}{2\times65000}=121 \text{ sq.ins.};$$

$$\text{Net length}=16.85;$$

$$\text{Depth}=\frac{121}{16.85}=7.2.$$

Add for slot, 1.5, making say, $8\frac{1}{2}$ ins.

Ampere Turns. Prepare a table as follows, the ampere turns per unit length being taken from tables or calculated by the usual formula.

Part.	Magnetic Density.	Length of Mean Line.	Ampere Turns per Inch.	Total Ampere Turns.
Field ring.........	79000	15	30	480
Pole core..........	100000	$15\frac{1}{2}$	80	1240
Air-gap...........	62500	$\frac{7}{16}$	20,400	8900
Teeth............	119500	$1\frac{1}{2}$	700	1050
Armature core.....	65000	10	12	120
Total				11790
Correction for teeth $1\frac{5}{8}$ instead of $1\frac{1}{2}$				90
Total				11880

Length of armature coil found to be 96 ins. =8 ft. Total length of each circuit is $27 \times 8 = 216$ ft. At all times there will be at least one coil out of each circuit, short circuited by the brush, so length of group of active coils is $26 \times 8 = 208$ ft. Watts lost per circuit $= \frac{1}{10}$ total $= 753$ watts.

$$\text{Current} = \frac{2400}{10} = 240;$$

$$C^2R = 735 = (240)^2R;$$

$$R = \frac{735}{(240)^2} = .0127 \text{ ohm hot } (40° \text{ C. rise});$$

$$R = .011 \text{ ohm cold.} \qquad R = \frac{L \times 10.6}{d^2};$$

$$d^2 = \frac{L \times 10.6}{R} = \frac{208 \times 10.6}{.011} = 200000 \text{ cm.}$$

Width of slot given was .38, say, $\frac{3}{8} = .375$.

1/32 staggering of teeth;
1/32 tape;
1/32 tape;
1/32 mica;
1/32 mica.

5/32, leaving 7/32 for copper.

200,000 cm. = 157,500 sq.m.

7/32 = 218.75 mils;

$$\text{Depth copper} = \frac{157500}{218.75} = 720 = .72 \text{ in.}$$

Depth of Slot.

$$\begin{array}{l} .72 \text{ copper;} \\ .72 \text{ copper;} \\ 1/32 \text{ tape;} \\ 1/32 \text{ tape;} \\ 1/16 \text{ between;} \\ 1/16 \text{ below;} \\ 1/16 \text{ below;} \\ \hline 1.69 \end{array}$$

Using a conductor 11/16 in. wide we get a depth of $1\frac{5}{8}$ in.

$$\text{Cir. mils in conductor} = \frac{687.5 \times 218.75}{.7859} = 192000,$$

$$\frac{192000}{240} = 800 \text{ cm. per amp.}$$

Armature also carries field current, hence current density would be slightly greater than this.

Field Winding. Shunt field current assumed as 1.5 per cent of total $= .015 \times 2400 = 36$ amp. Mean length of turn found to be 62 ins. $= 5.16$ ft.

$$t = 11{,}880 \div 36 = 325,$$

$$d^2 = \frac{36 \times 5.16 \times 325 \times 12.25}{125} = 59000 \text{ cm., say, No. 3.}$$

It is now found that the mean length of turn used above is not correct. Revised length $= 59\frac{1}{2}$ ins., say, 5 ft.

Then $L = 325 \times 5 \times 10 = 16250$ ft. $= 2440$ lbs.

Total series turn $=2840+600=3440$.

$$\frac{3440}{2400}=1.42 \text{ turns.}$$

To be sure to be on the safe side use $2\frac{1}{2}$ turns.

$$\frac{2400}{2.5}=960 \text{ amp.}$$

$$2400-960=1440 \text{ amp. to be diverted.}$$

C^2R loss in series field and jumper $=1870$ watts.

Total losses = arm C^2R =	7860
Hysteresis	2996
Eddy	378
Shunt C^2R	4500
Series C^2R	1870
	17604

$$\frac{300000-17604}{300{,}000}=94.13.$$

Electrical efficiency $=94.13$ per cent.
Commutator, 270 bars, 30 ins.

Diam. gives $\dfrac{50\times\pi\times 90}{12}=1175$ feet per min. (O.K.)

Thickness of bar $=\dfrac{50\times\pi}{270}-\text{mica}=.560-.047=.533.$

Bar pitch $=\dfrac{50\times\pi}{270}=.580.$

Brush pitch $= \frac{50 \times \pi}{10} = 15.7$ in.

Allowing brushes to cover approx. 10 per cent of brush pitch $= 1.57$ in.

This covers $\frac{1.57}{.580} = 2.7$ com. bars.

Making brush 1.5 thick gives $\frac{1.5}{.580} = 2.6 \times$ thickness of 1 bar, which is O.K.

Current per brush arm $= \frac{2400}{5} = 480$.

Using a current density of 25 amp. per square inch, this calls for $\frac{480}{25} = 19.2$ sq.in.

$\frac{19.2}{1.5} = 12.8$ ins.

If 6 brushes are used $\frac{12.8}{6} = 2.13$ ins. = width.

Better use 7, $\frac{12.8}{7} = 1.83$.

Make carbons $1\frac{1}{2} \times 1\frac{7}{8}$.

Allow $\frac{3}{8}$ in. for holders and clearance.

$7 \times 2\frac{1}{4} = 15\frac{3}{4}$.

Allowing 2 ins. for clearance and riser we get $17\frac{3}{4}$, say, 18 ins.

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